

THERMAL TRANSPORT IN THE DIII-D EDGE PEDESTAL

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Abstract

A new procedure for inferring $\chi_{i,e}^{\text{exp}}$ in the plasma edge from experimental data and integrated modeling code calculations has been developed which takes into account atomic physics and radiation effects and convective as well as conductive heat flux profiles. Application to DIII-D [J. Luxon, *Nucl. Fusion*, 42, 614 (2002)] shots indicates that proper inference of $\chi_{i,e}^{\text{exp}}$ in the edge pedestal (sharp gradient region) depends on accounting for the variation in electron and ion heat fluxes and in the convective fraction of each over the edge region. The frequently observed steep edge temperature gradients are found to depend as much on the variation in conductive and convective heat fluxes as on a reduction in $\chi_{i,e}$. Inferred $\chi_{i,e}^{\text{exp}}$ are compared with theoretical predictions.

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I. Introduction

The physics of the steep-gradient, edge pedestal region in H-mode ([high confinement mode](#)) plasmas has been the subject of experimental investigation for many years (e.g. Refs. 1-8). The motivation for understanding the edge pedestal is based, at least in part, on calculations^{9,10} which indicate that because of “stiffness” in temperature profiles the performance of future tokamaks will be sensitive to the value of the density and particularly the temperature at the top of the edge pedestal. Thus, understanding the edge pedestal characteristics is generally regarded to be a prerequisite for predicting the performance of future tokamaks.

Theoretical efforts to understand the edge pedestal have focused on several different aspects of the underlying physics. Investigations (e.g. Refs. 11-14) of the MHD stability of the edge pressure pedestal against ballooning and peeling (surface kink) modes have led to an understanding of edge pressure/pressure gradient limits leading to the onset of edge-localized-mode (ELM) instabilities which momentarily destroy the edge pedestal structure.

While the onset of MHD ([magnetohydrodynamic](#)) instabilities such as ELMs limit the maximum allowable value of the pressure or pressure gradient in the edge pedestal, they can not determine the structure of the pressure profile when the MHD instabilities are suppressed. Several other lines of investigation have been developed to the end of explaining (or at least modeling) the edge pedestal structure observed in the absence of or in between or averaged over ELMs. The interaction of the plasma ion and neutral atom profiles has been shown to produce an edge pedestal structure in the former, under the assumption of diffusive particle transport¹⁵. The physical conservation (particle, momentum, energy), transport and atomic physics constraints have been shown to require a pedestal structure in the edge temperature and density profiles that agrees with experimental observation, when experimental rotation velocity and radial electric field profiles are used to evaluate the predicted pinch velocity^{16,17}. A particle guiding center analysis¹⁸ has been employed to explain the pedestal formation in terms of the ionization of recycling neutrals, together with orbit squeezing and the presence of an X-point

transport mechanism. Finally, particle and energy diffusion coefficients have simply been adjusted in transport simulations of the plasma edge to obtain agreement with measured edge density and temperature profiles (e.g. Refs. 7, 8, 19 and 20). Other investigations have had the objective of combining MHD, transport and atomic physics mechanism to develop theory-based predictive algorithms for pedestal parameters such as width and height (e.g. Refs. 21 and 22).

The ion and electron thermal diffusivities are important parameters in any attempt to understand the edge temperature pedestals. Knowledge of these diffusivities to date comes almost entirely from their trial and error adjustment in transport simulations to obtain agreement with observed edge temperature profiles^{7,8,16,17,19,20}, although there have been some initial efforts to calculate edge thermal diffusivities from edge turbulence codes (e.g. Ref. 23). Such trial and error transport simulation fitting procedures are subjective, depend on the transport model and on the assumption about the split between convective and conductive heat fluxes, and do not provide much information about uncertainties in the inferred thermal diffusivities. Our purposes in this paper are 1) to present a more systematic procedure for inferring thermal diffusivities in the edge pedestal from experimental profile data, 2) to apply this procedure to DIII-D H-mode shots with different edge parameters in order to infer ion and electron thermal diffusivity profiles in the edge pedestals and to elucidate the edge phenomena that affect these inferences.

II. Particle and Energy Transport in the Edge Pedestal

We have previously shown^{16,17} that 1) the radial momentum balance requirement that the ion pressure gradient balances the forces due to the $V \times B$ and E_r forces

$$\frac{\partial p_i}{\partial r} = n_i e_i \left(E_r + V_{\theta i} B_\phi - V_{\phi i} B_\theta \right), \quad (1)$$

and the use of the toroidal momentum balance leads to the requirement that the ion pressure gradient drive an outward ion flux that is sufficiently larger than the inward

“pinch” ion flux (driven primarily by the radial electric field and rotation) that the net outward ion flux satisfies the requirement of the continuity equation. This leads to a particle transport relation

$$L_{pi}^{-1} \equiv -\frac{1}{p_i} \frac{\partial p_i}{\partial r} = \frac{V_{ri} - V_{pinch}}{D_i} \quad (2)$$

where $V_{ri} = \Gamma_i / n_i$ and

$$V_{pinch,i} = \frac{\left[-M_{\phi i} - n_i e_i E_{\phi}^A + n_i m_i (v_{il} + v_{di}^*) \left(f_p^{-1} V_{\theta i} + \frac{E_r}{B_{\theta}} \right) - n_i m_i v_{il} V_{\phi l} \right]}{n_i e_i B_{\theta}} \quad (3)$$

is of the form of a pinch velocity that can be evaluated using $M_{\phi i}$, the external momentum input (e.g. from neutral beams), E_{ϕ}^A , the induced toroidal electric field, v_{il} , the interspecies collision frequency, v_{di}^* the total frequency for radial momentum transfer by viscous, inertial, atomic physics and ‘anomalous’ processes, $f_p \equiv B_{\theta} / B_{\phi}$, and the measured radial electric field and impurity toroidal rotation velocity. The only quantity that must be determined non-experimentally is the main ion poloidal rotation velocity, which can be estimated from the measured impurity poloidal rotation velocity or calculated. The quantity

$$D_i = \frac{m_i T_i v_{il}}{(e_i B_{\theta})^2} \left[1 + \frac{v_{di}^*}{v_{il}} - \frac{Z_i}{Z_I} \right] \quad (4)$$

is of the form of a diffusion coefficient.

When measured rotation velocities and electric fields were used to evaluate Eq. (3) and thermal transport coefficients inferred from experiment were used to evaluate L_{Ti} , we have found¹⁷ for several H-mode DIII-D shots that using Eq. (2) to integrate $-1/n_i (\partial n_i / \partial r) = L_{pi}^{-1} - L_{Ti}^{-1}$ yielded edge pedestal density profiles in good agreement with measured profiles. Thus, the next logical topics in this line of investigation would seem to be understanding the thermal and momentum transport and calculating rotation and the radial electric field in the edge plasma. This paper presents a more detailed investigation of thermal energy transport in the edge pedestal region of DIII-D H-mode plasmas. (Plans

for further investigation of momentum transport and the calculation of the electric field and rotation velocities in the edge plasma region are under development.)

The total ion and electron radial heat fluxes consist of conductive and convective components

$$Q_{i,e} = n_{i,e} T_{i,e} \chi_{i,e} L_{Ti,e}^{-1} + \frac{5}{2} \Gamma_{i,e} T_{i,e} \quad (5)$$

Thus, if $n_{i,e}$, $T_{i,e}$ and $L_{Ti,e}^{-1}$ are determined experimentally and $Q_{i,e}$ and $\Gamma_{i,e}$ are calculated from heat and particle balances, the experimental $\chi_{i,e}$ profile can be evaluated from

$$\chi_{i,e}(r) = L_{Ti,e}(r) \left[\frac{Q_{i,e}(r)}{n_{i,e}(r) T_{i,e}} - \frac{5}{2} \frac{\Gamma_{i,e}(r)}{n_{i,e}(r)} \right] \quad (6)$$

We note that this inference of $\chi_{i,e}$ depends not only on the measured temperature and density profiles and the total heat flux $Q_{i,e}$, but also on the convective heat flux.

We use an integrated modeling code system²⁴ that performs i) particle and power balances on the core plasma to determine the net particle and heat fluxes outward across the separatrix, which are used as input to ii) an extended 2-point divertor model (with radiation and atomic physics) that calculates plasma densities and temperatures in the divertor and SOL and the ion flux incident on the divertor plate, which iii) is recycled as neutral molecules and atoms that are transported (2D) through the divertor region across the separatrix into the plasma edge region. Any sources of gas puffed neutrals are also similarly transported inward. This integrated code system is used to calculate the ion particle and total heat fluxes crossing the separatrix from the core into the SOL ([scrape-off layer](#)): $\Gamma_{sep} = \text{beam particle source} + \text{recycling neutral particle source}$, $Q_{sep} = \text{beam} + \text{ohmic power input} - \text{core radiation}$. In general, time derivative terms should be added to the balance, but we have chosen times in shots for which time derivatives averaged over tens of ms are small. We must at present estimate the split of Q_{sep} into Q_{sepi} and Q_{sepe} .

Using these values from the integrated model calculation as separatrix boundary conditions, we can then integrate the plasma ion particle balance equation

$$\frac{\partial \Gamma}{\partial r} = n_e n_o \langle \sigma v \rangle_{ion} + S_{nb}, \quad \Gamma(r_{sep}) = \Gamma_{sep}^{exp} \quad (7)$$

where n_o is the density of recycling and gas fueling neutrals and S_{nb} is the source rate of plasma ions due to neutral beam (and pellet) injection, and the heat balance equations

$$\frac{\partial Q_i}{\partial r} = q_{nbi} - \frac{3}{2}(T_i - T_o^c)n_i n_o^c \langle \sigma v \rangle_{cx+el} - q_{ie}, \quad Q_i(r_{sep}) = Q_{sepi}^{\text{exp}} \quad (8a)$$

and

$$\frac{dQ_e}{dr} = q_{nbe} + q_{ie} - n_e n_o \langle \sigma v \rangle_{ion} E_{ion} - n_e n_z L_z, \quad Q_e(r_{sep}) = Q_{sepe}^{\text{exp}} \quad (8b)$$

inward from the separatrix to determine the edge distributions of $\Gamma(r)$ and $Q_{i,e}(r)$ needed to evaluate the radial distribution of $\chi_{i,e}$ from Eq. (6). Here $q_{nbi,e}$ is the local neutral beam power deposition density, n_o is the recycling neutral density, n_o^c is the density of ‘cold’ recycling neutrals that have not yet collided inside the separatrix and $1.5T_o^c$ is their average energy, $q_{ie} \sim (T_i - T_e)/T_e^{1.5}$ is the ion-electron equilibration rate, $E_{ion}(T_e, n_e)$ is the ionization energy, n_z is the impurity (carbon) density, $L_z(T_e, n_o)$ is the impurity radiation emissivity, $\langle \sigma v \rangle_{cx+el}(T_i)$ is the charge-exchange plus elastic scattering rate coefficient, and $\langle \sigma v \rangle_{ion}(T_e, n_e)$ is the electron impact ionization rate coefficient. The experimental $n_{e,z}$ and $T_{i,e}$ and the calculated neutral density are used to evaluate the terms in Eqs. (7) and (8), which are then integrated radially inward from the experimental separatrix boundary conditions for the particle and heat fluxes determined as discussed above. The atomic physics data are taken from Ref. [25] (subsequent extensions to higher temperatures), and the radiation emissivity is calculated from a fit to coronal equilibrium calculations (taking into account the effect of charge-exchange and recombination in the presence of recycling neutrals) based on the ADPAC data²⁶.

III. Thermal Analysis of the Edge Pedestal in DIII-D H-Mode Shots

A. Edge density and temperature profiles

Three ELMing H-mode shots with a range of edge parameters were chosen for detailed analysis. Shot 92976 ($P_{nb} = 5.0$ MW, $\delta = .33$, $q_{95} = 5.7$, $n_{carb}/n_D = 1.5\%$) was a heavily gas puffed shot with a strong density pedestal and relatively low edge temperatures at 3212 ms just before MARFE'ing ([multifaceted asymmetric radiation from the edge](#)) and making a H-L back transition immediately thereafter. Shot 97979 ($P_{nb} = 6.5$ MW, $\delta = .75$, $q_{95} = 3.9$, $n_{carb}/n_D = 2.0\%$) was also a strongly gas puffed shot with high triangularity, sharp density and T_e pedestals and somewhat higher edge temperatures than shot 92976. It was in the middle of a robust H-mode phase at 3250 ms. Shot 118583 ($P_{nb} = 9.2$ MW, $\delta = .37$, $q_{95} = 3.8$, $n_{carb}/n_D = 6.0\%$) was a lower density discharge with high pedestal temperatures, and was also **heavily** gas fueled **at 2000 ms**. **The electron density and temperature data were measured with Thomson scattering, and the ion temperature was measured with charge-exchange recombination spectroscopy of C VI.** Pedestal density and temperatures and high order spline fits thereto **calculated by the standard GAPROFILES data analysis code** are shown in Figs. 1-3. The gradient scale lengths L_{ne} and $L_{Ti,e}$ were constructed from these spline fits.

To further characterize the plasma edge region, the parameters $\nu_{ei}^* \equiv \nu_{ei} \nu_{the} / qR$ and $\eta_{i,e} \equiv \frac{1}{T_{i,e}} \frac{\partial T_{i,e}}{\partial r} \bigg/ \frac{1}{n_{i,e}} \frac{\partial n_{i,e}}{\partial r}$ are shown in Fig. 4. The sharp decrease in $\eta_{i,e}$ in the pedestal region in shots 92976 and 97979 results from the much stronger density than temperature gradient. In shot 118583, $\eta_e \approx 2$ over the entire edge region, in agreement with the result reported for ASDEX-U⁷, but this was not the case for the other two shots.

All three shots were experiencing ELMs about every 10 ms at the times examined. The time selected **for analysis** was just (about 1 ms) before an ELM for two of the shots and about midway between ELMs for the third shot, as determined by D_α data. **By examining data taken at nearby times, it was determined that** the measured pedestal densities and temperatures were about constant averaged over several ELM periods, and the times chosen for analysis had pedestal values representative of this average. Moreover, the **ion temperature** data were averaged values over 10 ms. The ELMs produced transients in the pedestal densities and temperatures, of course, but since the

pedestal densities and temperatures averaged over several ELMS were near constant in these shots, the dn/dt and dW/dt terms average out over times comparable to the ELM period. Thus, it is appropriate to consider the results of this analysis as being averaged over ELMS.

B. Edge cooling and heating profiles

The charge-exchange (plus elastic scattering) cooling rates of the plasma ions by cool incident neutrals from the plenum and scrape-off layer and the cooling rates of the plasma electrons by electron-impact ionization of incident neutrals and by radiation (line and recombination radiation of the carbon impurity and bremsstrahlung) are shown in Fig. 5 for the three shots. The edge peaking of the charge-exchange and ionization cooling are determined largely by the edge attenuation of uncollided (cool) and total calculated neutral influxes, respectively. The edge peaking of the radiation cooling is due to a combination of lower temperature and charge-exchange/recombination enhancement of the carbon radiation due to the high edge neutral concentration. The edge peaking of radiation cooling is larger for the low edge temperature shot 92976 than for the other two shots with higher pedestal electron temperatures. The radiation cooling is more important than the charge-exchange or ionization cooling except for the region just inside the separatrix in the low density shot 118583. The non-monotonic nature of q_{ie} is an artifact of using the experimental $T_{i,e}$ profiles. **For those shots for which the temperature pedestal location is clearly discernible,** there is no obvious correlation between the location of the pedestal in the electron temperature profile and either the radiation cooling or ionization cooling profiles, nor between the pedestal in the ion temperature profile and the peaking in the charge-exchange cooling profile.

C. Edge heat and particle flux profiles

These edge cooling phenomena significantly affect the edge profiles of $Q_{i,e}$ in the low-temperature/high-density shot 92976, but have relatively less effect in the other shots

with higher edge temperatures and lower edge densities, as shown in Figs. 6. The ionization of incident neutrals has a large effect on the edge profile of Γ_i , as also shown in Figs. 6.

The magnitudes of $Q_{i,e}$ depend on net heat input to the core plasma and on the split between the electron and ion heat removal channels, **the latter of which** presently can not be determined experimentally. However, the particle fluxes $\Gamma_{i,e}$ can be determined from the integrated modeling code, as discussed above. For a given convective heat flux ($\frac{5}{2}\Gamma_{i,e}T_{i,e}$) profile, a range of physically allowable values of the ion-electron energy flux split, as characterized here by the parameter $(Q_e/(Q_e + Q_i))_{sep}$, can be determined from the requirement that the conductive heat fluxes must be everywhere non-negative. In our calculations, this condition requires that $(Q_e/(Q_e + Q_i))_{sep}$ be in the relatively narrow bands $0.50 \leq (Q_e/Q)_{sep} \leq 0.60$ for shot 92976 and $0.45 < (Q_e/Q)_{sep} < 0.55$ for shot 118583, but only within the relatively broad band $0.40 \leq (Q_e/Q)_{sep} \leq 0.80$ for shot 97979. The broader range of allowable values of $(Q_e/Q)_{sep}$ for shot 97979 than for the other two shots results from the significantly lower value of $\Gamma_{i,e}$ for this shot than for the other two.

The $Q_{i,e}$ profiles corresponding to limiting values of the allowable range of $(Q_e/Q)_{sep}$ are shown in Figs. 6. **For shot 118583 the allowable range was very narrow $0.45 < (Q_e/Q)_{sep} < 0.55$, and only the value for $(Q_e/Q)_{sep} = 0.50$ is shown. The ion heat flux decreased with radius in all shots, and the electron heat flux increased with radius, both due primarily to ion heating of electrons (Figs. 5).**

D. Edge convective heat flux fraction profiles

Corresponding to each value of the possible energy split within the allowable range of $(Q_e/(Q_e + Q_i))_{sep}$ there is a different split between the convective and conductive

fractions of both the ion and electron heat fluxes. The convective fractions, $f_{conv}^{i,e} \equiv (2.5\Gamma_{i,e} T_{i,e})/Q_{i,e}$, of the ion and electron energy fluxes are plotted in Figs. 7, for the limiting values of $(Q_e/(Q_e + Q_i))_{sep}$ (again except for shot 118583). The peaking of the convective energy fluxes and convective fractions just inside the separatrix is due to the ionization of incident neutrals.

For values of $(Q_e/(Q_e + Q_i))_{sep}$ larger than the upper limiting value [e.g. $(Q_e/(Q_e + Q_i))_{sep} > 60\%$ for shot 92976] the total ion heat flux would become smaller than the convective ion heat flux and the ion convective fraction would become unphysical ($f_{conv}^i > 1$) just inside the separatrix, as shown in Fig. 7a. For values of $(Q_e/(Q_e + Q_i))_{sep}$ smaller than the lower limiting value [e.g. $(Q_e/(Q_e + Q_i))_{sep} < 50\%$ for shot 92976] the total electron heat flux would become smaller than the convective electron heat flux and the electron convective fraction would become unphysical ($f_{conv}^e > 1$) in the flattop region, as also shown in Fig. 7a. Similar results are shown for shot 97979 in Fig. 7b. **Note that for shots 92976 and 97979 the actual bounds are slightly narrower than the cases shown for which the convective fractions actually exceed unity.**

It is clear from Figs. 7 that convective heat transport likely dominates conductive heat transport (convective fraction > 0.5) for ions and/or electrons over some portion of the plasma edge and that the convective/conductive split varies with radius. This has profound implications for the inference of $\chi_{i,e}$, calling into question inferences based on the common assumption that the heat flux is entirely conductive.

E. Edge heat diffusivity profiles

The profiles of $\chi_{i,e}^{exp}$ inferred by using the experimental temperature and density profiles and the calculated heat and particle fluxes used to evaluate Eq. (6) are shown in Figs. 8 and 9, for the limiting (92976, 97979) or median (118583) values of the allowable range of $Q_{esep}/(Q_i + Q_e)_{sep}$. The experimental values of $\chi_{i,e}^{exp}$ must fall within the bounds formed by these limiting profiles. Also shown are the profiles of $\chi_{i,e}$ calculated from

various approximate theoretical expressions (see appendix) using the experimental density and temperature data.

The experimentally inferred $\chi_{i,e}^{\text{exp}} = L_{T_{i,e}}(1 - f_{\text{conv},e})Q_{i,e}/n_{i,e}T_{i,e}$ shown in Figs. 8 and 9 depend on the heat fluxes shown in Figs. 6 and on the convective heat flux fractions f_{conv} shown in Figs. 7, both of which clearly vary with position across the edge region. For shot 92976 there are clearly discernible steep gradient regions for both electron (Fig. 1b) and ion (Fig. 1c) temperatures for $\rho > 0.95$. The electron heat flux generally increased with radius (Fig. 6a) over the entire edge (due to ion heating), and the convective heat flux fraction for electrons (Fig. 7a) decreased over $0.95 > \rho > 0.97-0.98$. The decreasing convective heat flux fraction, the increasing heat flux, and the decreasing density and temperature all contributed to the steep-gradient; i.e. to the small value of $L_{Te} = \chi_e^{\text{exp}} n_e T_e / (1 - f_{\text{conve}}) Q_e$. The inferred χ_e^{exp} is actually increasing for $\rho > 0.95$. The ion heat flux (Fig. 6a) decreased with radius (due primarily to ion heating of the electrons) and the convective heat flux fraction for ions (Fig. 7a) was constant or increasing for $\rho > 0.95$. The decreasing ion heat flux and increasing convective heat flux fraction would tend to decrease the ion temperature gradient; i.e. increase $L_{Ti} = \chi_i^{\text{exp}} n_i T_i / (1 - f_{\text{conv}i}) Q_i$, while the decreasing density and temperature would tend to increase the ion temperature gradient. The resulting inferred $\chi_i^{\text{exp}} = L_{Ti}(1 - f_{\text{conv}i}) Q_i / n_i T_i$ (Fig. 8a) decrease with radius to produce the steep ion temperature gradient for $\rho > 0.95$.

For shot 97979, there is a sharp-gradient region for the electron temperature for $\rho > 0.95$, but the ion temperature gradient is relatively constant over the edge region (Figs. 2b and 2c). The electron heat flux increased (Fig. 6b) and the conductive electron heat flux fraction decreased (Fig. 7b) with radius over $\rho > 0.95$, both contributing to a steep electron temperature gradient; i.e. a small value of $L_{Te} = \chi_e^{\text{exp}} n_e T_e / (1 - f_{\text{conve}}) Q_e$. The inferred $\chi_e^{\text{exp}} = L_{Te}(1 - f_{\text{conve}}) Q_e / n_e T_e$ actually increased over $\rho > 0.95$ (Fig. 9b). The ion heat flux decreased (Fig. 6b), and the convective fraction of the ion heat flux increased (Fig. 7b), over $\rho > 0.95$, both tending to decrease the temperature gradient; i.e. make $L_{Ti} = \chi_i^{\text{exp}} n_i T_i / (1 - f_{\text{conv}i}) Q_i$ larger. These factors and the decreasing with radius ion

density and temperature combined to produce the experimentally inferred increasing $\chi_i^{\text{exp}} = L_{Ti} (1 - f_{\text{conv}i}) Q_i / n_i T_i$ shown in Fig. (8b).

For shot 118583 both the ion and electron temperature gradients were relatively constant over the edge (Figs. 3b and 3c), although there may be a slight pedestal for $\rho > 0.92$. Both the ion and electron heat fluxes were relatively uniform, with a slight increase in the electron heat flux and decrease in the ion heat flux at the very edge (Fig. 6c). The convective heat flux fractions for both ions and electrons decreased with radius across the edge region, except for an upturn in the ion convective fraction for $\rho > 0.98$ (Fig. 7c). These effects and the decreasing densities and temperatures combined to produce an inferred $\chi_{i,e}^{\text{exp}} = L_{Ti,e} (1 - f_{\text{conv}i,e}) Q_{i,e} / n_{i,e} T_{i,e}$ that increased with radius across the edge region (Figs. 8c and 9c).

The same experimental temperature and density profiles were used to evaluate Eq. (6) when the assumption of radially uniform conductive heat flux **and zero convective heat flux** was made. For all three shots, sharp dips in $\chi_{e,i}^{\text{exp}}$ in the sharp-gradient pedestal region were calculated, as contrasted to the **smaller dips or increase in $\chi_{e,i}^{\text{exp}}$ inferred with the more accurate calculations** taking into account also the profiles of the conductive and convective heat fluxes. **For example, the inferred χ_e^{exp} with the uniform conductive heat flux assumption dipped by a factor of 3-5 in the steep gradient region for all three shots, while the inferred χ_e^{exp} taking into account the variation in convective and conductive heat fluxes dipped significantly less in the sharp gradient region for shots 92976 and 97979, and actually increased for shot 118583.** Thus, the ion and electron temperature profiles in the edge pedestal (sharp gradient region) appear to be associated as much, if not more, with an increase in the electron heat flux with radius, a decrease in the ion heat flux with radius and a reduction in the convective heat flux fraction of both with radius, as with a reduction in $\chi_{i,e}$ with radius.

Profiles of theoretical $\chi_{e,i}^{\text{th}}$, based on using the experimental density and temperatures to evaluate the simple analytical formulas given in the appendix, are also given in Figs. 8 and 9. The neoclassical value, χ_i^{neo} , falls somewhat below the

experimentally inferred range for χ_i^{exp} throughout most of the edge region for shots 92976 and 118583, and somewhat above the experimentally inferred range for shot 97979, in reasonable agreement overall. Orbit squeezing corrections²⁷ (not included) would reduce χ_i^{neo} in the very edge. The η_i – **mode** prediction is as much as an order of magnitude below the experimentally inferred range for shot 92976 and as much as an order of magnitude above for shot 118583 (except in the steep-gradient pedestal region), but is in reasonable agreement with experiment for shot 97979.

The trapped electron mode (TEM) χ_e^{TEM} generally over-predicts the experimentally inferred χ_e^{exp} for the higher temperature shots 97979 and 118583, but is in reasonable agreement for the lower temperature shot 92976. The resistive ballooning mode predictions are generally “in the ballpark” of the inferred range for χ_e^{exp} .

These predictions of $\chi_{i,e}$ based on the simple theoretical expressions given in the appendix can only provide a rough indication of the level of transport associated with the associated causative phenomenon. More sophisticated calculations are needed for a detailed comparison of theory and experiment, but this is beyond the scope of this paper.

F. Discussion of uncertainties

The range of $\chi_{i,e}^{\text{exp}}$ values determined above is sensitive to the ion-electron energy flux split (characterized here by the value of $(Q_e/(Q_e + Q_i))_{\text{sep}}$) and to the value of the convective heat flux. The ion-electron energy flux split in the edge depends on the energy transport and exchange in the core and can, in principle, be calculated if the energy transport and exchange mechanisms in the core are correctly modeled. We do not yet have available such a modeling capability that has been sufficiently checked against experiment, nor are we aware of such existing elsewhere. Also, as far as we know, no one has yet devised an experimental determination of the ion-electron energy flux split in the plasma edge. Further computational and experimental efforts to determine the ion-electron energy flux split in the plasma edge could provide the means to further narrow the range of uncertainty in the experimentally inferred $\chi_{i,e}^{\text{exp}}$.

Evaluation of the convective energy flux is rightfully regarded as difficult and uncertain, and we have taken pains with this aspect of the calculation. The particle flux in the edge was calculated by integrating the continuity equation inward from a separatrix ion particle flux boundary condition determined from a global particle balance on the plasma. The particle sources were from the neutral beams, which can be calculated accurately, and from the neutral influx resulting from gas fueling and recycling of plasma ions, which we calculated with a 2D neutral transport model. We used ion fluxes from the plasma into the SOL to calculate incident ion fluxes on the divertor plate (with a “2-point” model including atomic physics and radiation) and used calculated charge-exchange neutral fluxes from the plasma edge, SOL and divertor to the wall to calculate neutral recycling from the chamber walls. The plasma flux into the SOL was calculated (iteratively) from the neutral beam and neutral influx fueling sources, using a “die-away” measurement²⁸ of particle confinement time in DIII-D. The fueling source was adjusted slightly **in the plenum region between the SOL and the wall** to account for wall outgassing or absorption and modeling imperfections so that the overall calculation predicted the measured line averaged density (i.e. the core fueling was correctly calculated). This neutral influx calculation has been found to be in reasonable agreement with measurements and Monte Carlo calculations in two DIII-D shots²⁹. Nevertheless, experiments which provided for further validation of the neutral influx calculation would increase the confidence in the calculation of the convective heat flux and hence of the inference of $\chi_{i,e}^{\text{exp}}$ in the plasma edge.

Finally, the spline fit of the data used in the analysis may introduce some uncertainty. For example, the spline fit to the density profile appears visually to be somewhat steeper than the data in the pedestal region for shot 92976, which would cause an underestimation of L_n in the steep-gradient region for this shot. The main effect would be to increase the $\eta_{e,i}$ curves for $\rho > 0.97$ by perhaps as much as a factor of 2 in Fig. 4a. The other effect would be on the neutral penetration calculation, but since an error in the plasma density would cause a compensating error in neutral density in the products of the plasma and neutral densities that enters the cooling terms in the equations for $Q_{i,e}$ the error on the determination of $\chi_{i,e}^{\text{exp}}$ is small.

IV. SUMMARY AND CONCLUSIONS

An improved procedure for inferring $\chi_{i,e}^{\text{exp}}$ in the plasma edge from measured temperature and density profiles and from the complementary results of an integrated modeling code has been developed and applied to three DIII-D H-mode shots. The procedure takes into account atomic physics and radiation effects on the edge particle and heat flux profiles, calculates both the convective and conductive electron and ion heat flux profiles, determines physically allowable values of the unknown split between the ion and electron heat fluxes in the edge, and infers therefrom a range of physically allowable $\chi_{i,e}^{\text{exp}}$ profiles.

It was found that convective heat transport varied radially and likely dominates conductive heat transport ($f_{\text{conv}} > 0.5$) over some portion of the plasma edge, which has profound implications for the inference of $\chi_{i,e}^{\text{exp}} = L_{Ti,e} (1 - f_{\text{conv}}) Q_{i,e} / n_{i,e} T_{i,e}$ and calls into question inferences based on the common assumption that the heat flux is entirely conductive ($f_{\text{conv}} = 0$) and constant over the edge region. The ion and electron temperature profiles in the edge pedestal (sharp gradient region) appear to be associated as much, if not more, with an increase in the electron heat flux, a decrease in the ion heat flux and a reduction in the convective heat flux fraction of both, as with a reduction in $\chi_{i,e}$.

Comparison of $\chi_{i,e}^{\text{exp}}$ profiles with the predictions of simple analytical transport models showed that both neoclassical and, to a lesser degree, η_i – mode theories for ion transport were in rough agreement with χ_i^{exp} , in magnitude if not profile, while the resistive ballooning mode theory was generally in better agreement with measured χ_e^{exp} than was the TEM theory for electron transport.

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APPENDIX: THEORETICAL χ 's

Neoclassical

The neoclassical expression for the ion thermal conductivity is³⁰

$$\chi_i^{neo} = \varepsilon^{1/2} \rho_{i\theta}^2 v_{iz} \quad (\text{A1})$$

In the presence of a strong shear in the radial electric field, the particle banana orbits are squeezed, resulting in a reduction in the ion thermal conductivity by a factor of $S^{-3/2}$, where²⁷

$$S = \left| 1 - \rho_{i\theta} \left(\frac{d \ln E_r}{dr} \right) \left(\frac{E_r}{v_{thi} B_\theta} \right) \right| \quad (\text{A2})$$

Here $\rho_{i\theta}$ is the ion poloidal gyroradius.

Ion temperature gradient modes

For a sufficiently large ion temperature gradient ($L_{Ti} < L_{Ti}^{crit} \approx 0.1R$) the toroidal ion temperature gradient (ITG) modes become unstable. An estimate of the ion thermal conductivity due to ITG modes is³¹

$$\chi_i^{itg} = \frac{5}{2} \left(\frac{1}{RL_{Ti}} \right)^{1/2} \left(\frac{T_e}{m_i} \right) \left(\frac{m_i}{e_i B} \right) \frac{1}{2} \rho_i \quad (\text{A3})$$

where ρ_i is the gyroradius in the magnetic field B , and $k_\perp \rho_i = 2$ has been used..

Electron drift waves

The principal electron drift wave instabilities with $k_\perp c_s \leq \Omega_i$ arise from trapped particle effects when $v_e^* = v_e / (v_{the} / qR) \varepsilon^{3/2} < 1$. In more collisional plasmas the mode becomes a collisional drift wave destabilized by passing particles. An expression for the electron thermal conductivity that encompasses both the dissipative trapped electron mode (TEM) and the transition to the collisionless mode as $v_e^* \rightarrow 0$ is given by³⁰

$$\chi_e = \frac{5}{2} \frac{\varepsilon^{3/2}}{\nu_e} \frac{c_s^2 \rho_s^2}{L_n L_{Te}} \left(\frac{1}{1 + 0.1/\nu_e^*} \right) \quad (\text{A4})$$

where c_s is the sound speed and $\rho_s = c_s/\Omega_i$, with Ω_i being the ion cyclotron frequency.

Resistive ballooning modes

Resistive ballooning modes can become unstable in the plasma edge, leading to a predicted thermal conductivity^{32,33}

$$\chi_e^{RB} = \frac{R}{L_n} (q\rho_e)^2 \nu_{ei} \quad (\text{A5})$$

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FIGURE TITLES

1. Measured edge density and temperatures for shot 92976. (Solid line is spline fit.)
2. Measured edge density and temperatures for shot 97979. (Solid line is spline fit.)
3. Measured edge density and temperatures for shot 118583. (Solid line is spline fit.)
4. Collisionality parameter, η_i and η_e evaluated with measured density and temperatures.
5. Edge cooling and heating rates evaluated with measured density and temperatures. (cxcool—charge-exchange cooling, ioncool—ionization cooling, radcool—radiation cooling, nbheate—neutral beam heating of electrons, nbheati—neutral beam heating of ions, q_{ie} —ion-electron energy exchange)
6. Calculated edge heat and particle fluxes.
7. Calculated convective fractions of electron and ion edge heat fluxes.
8. Experimentally inferred and theoretical ion heat diffusivities in plasma edge.
9. Experimentally inferred and theoretical electron heat diffusivities in plasma edge.

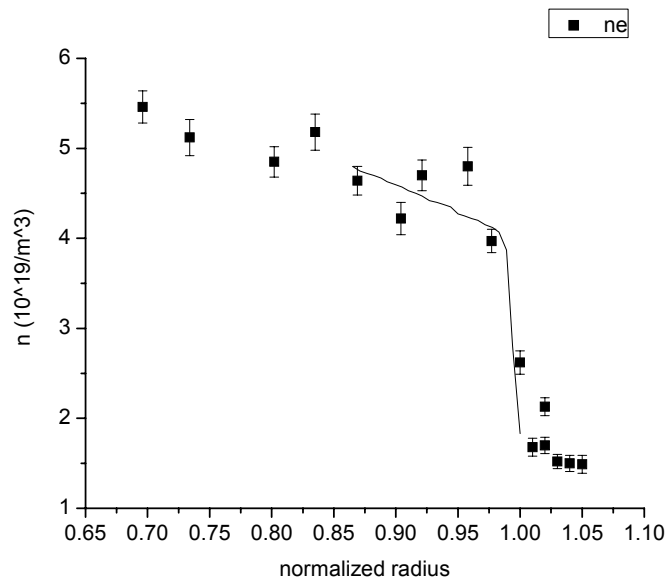


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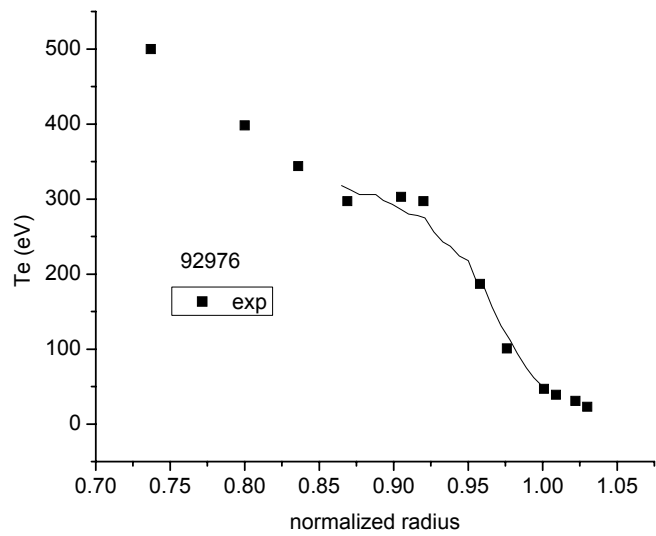


Fig. 1.b

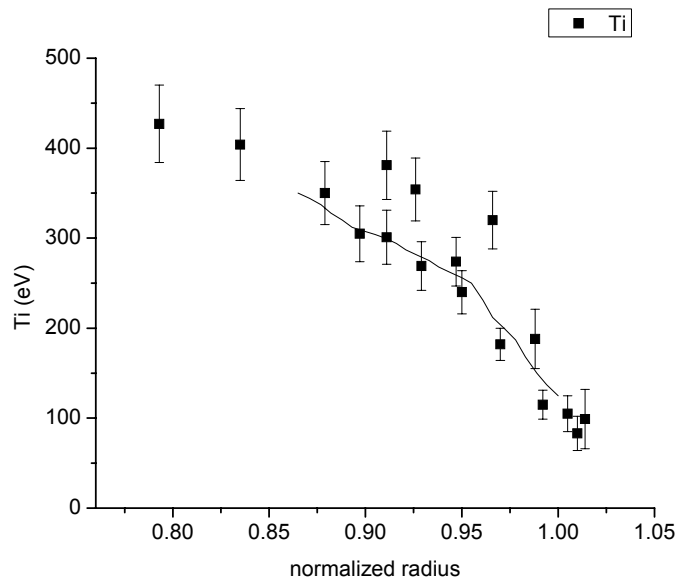


Fig. 1.c

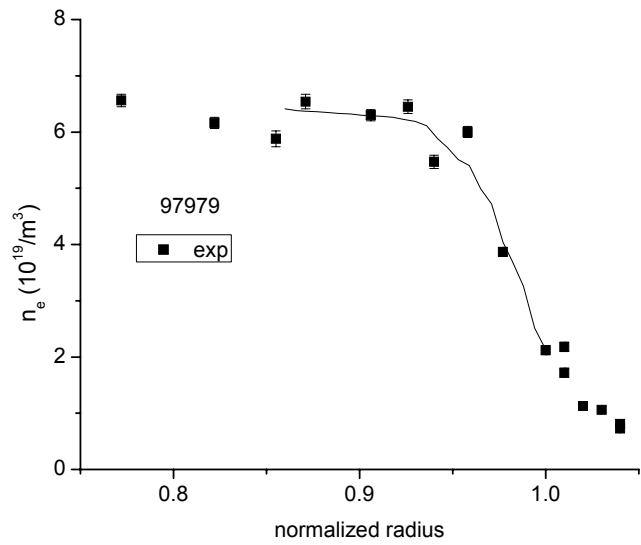


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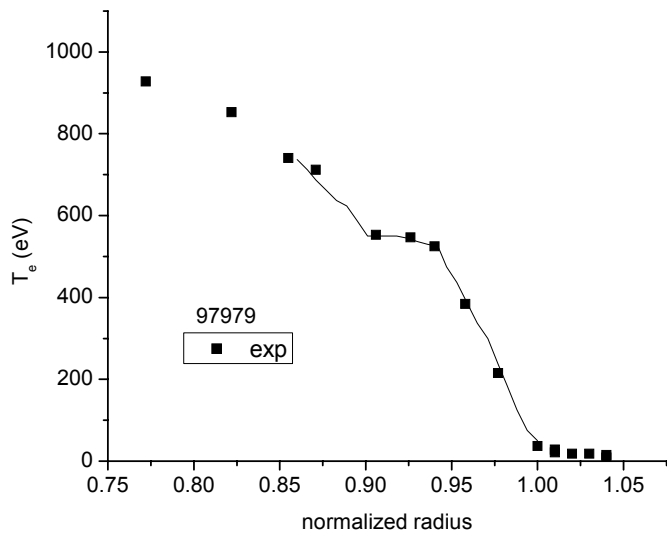


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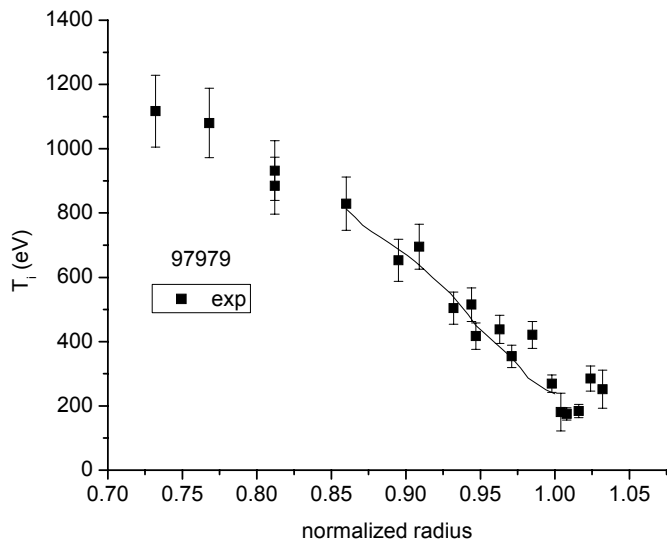


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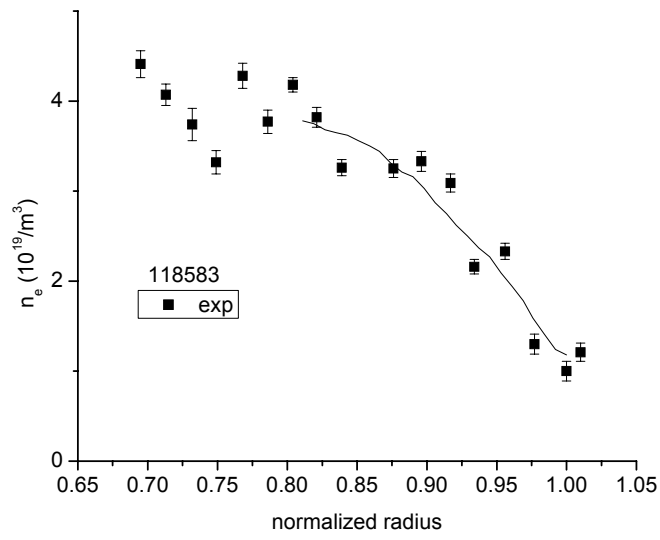


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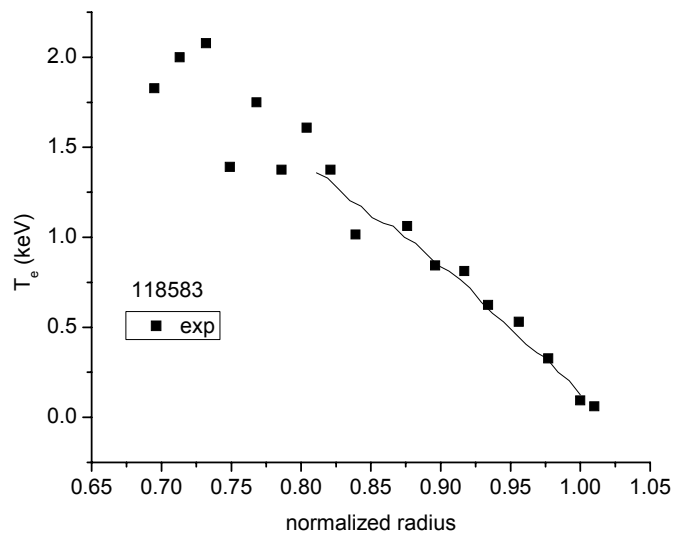


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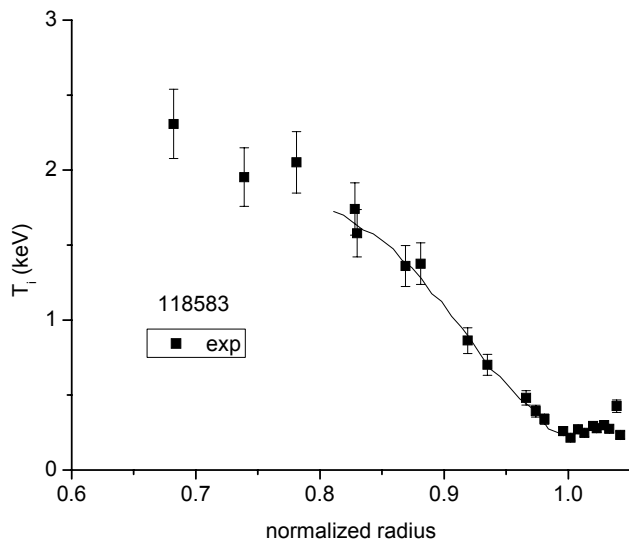


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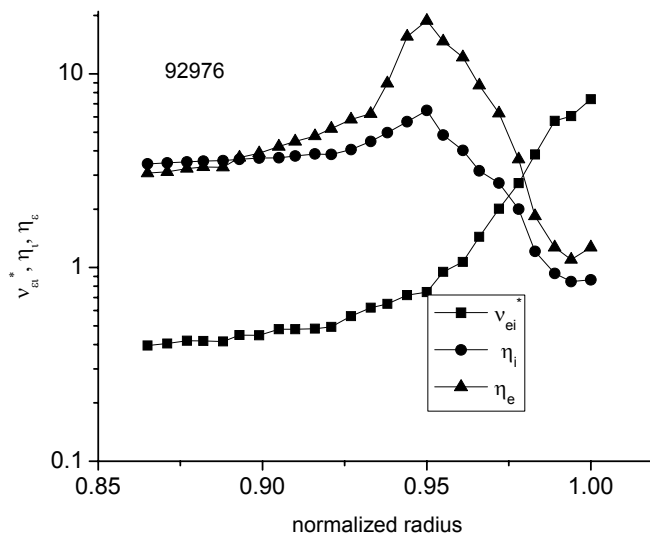


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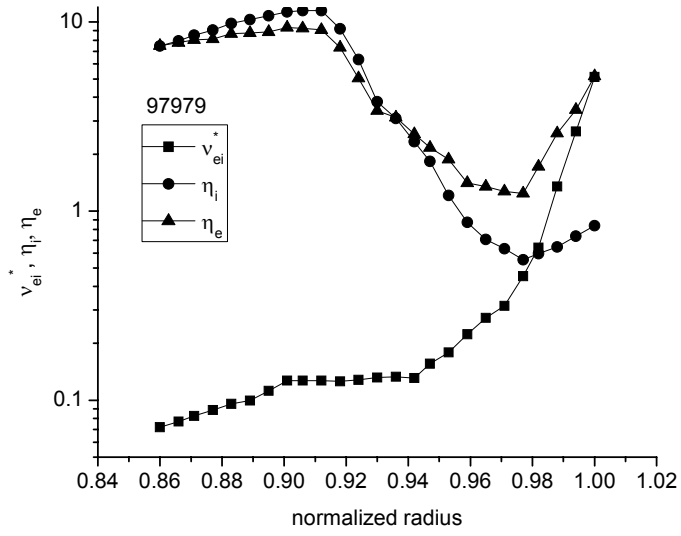


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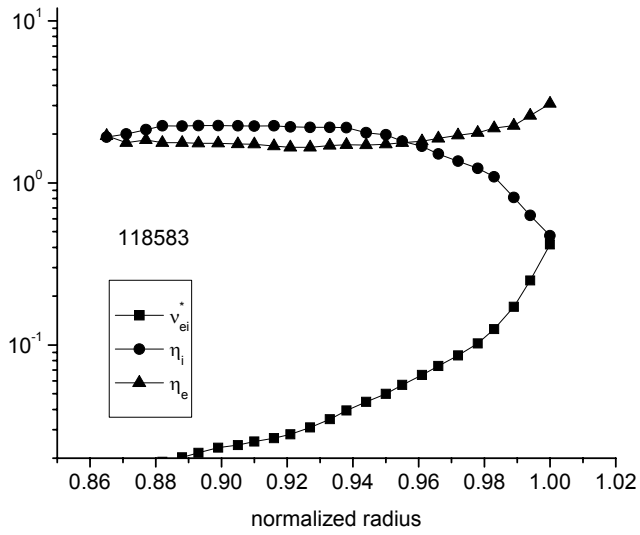


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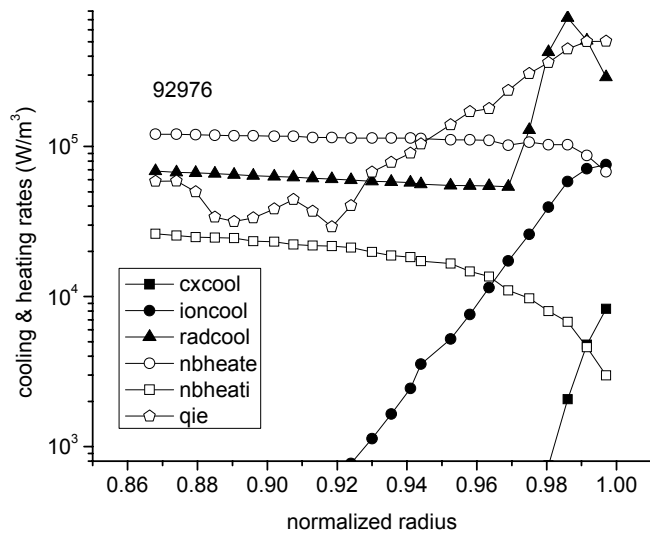


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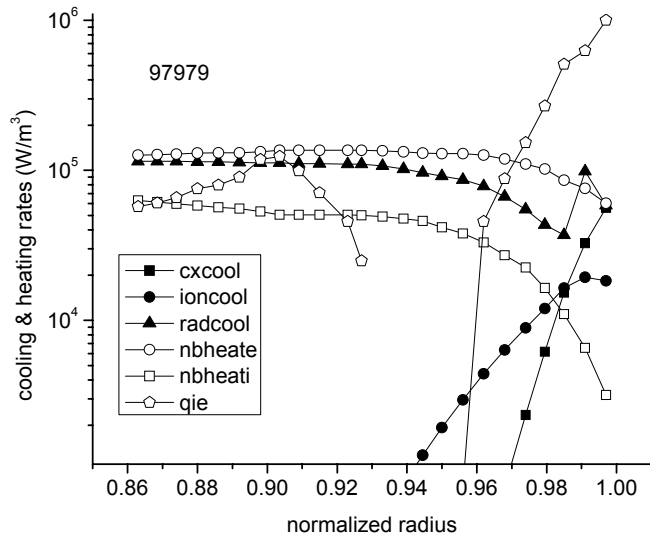


Fig. 5b

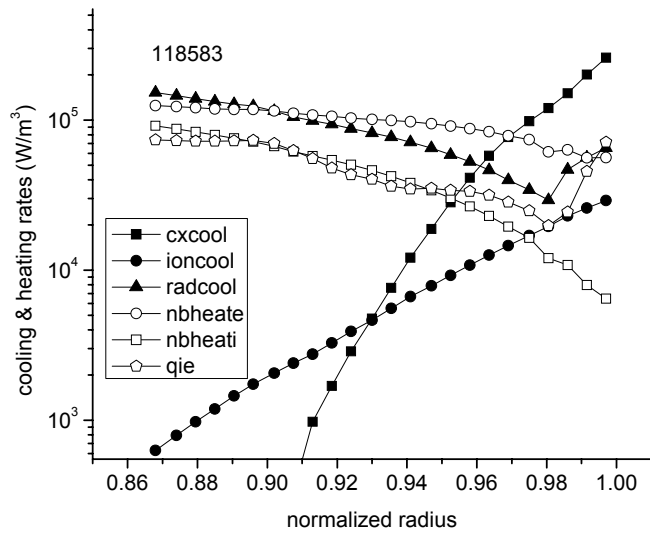


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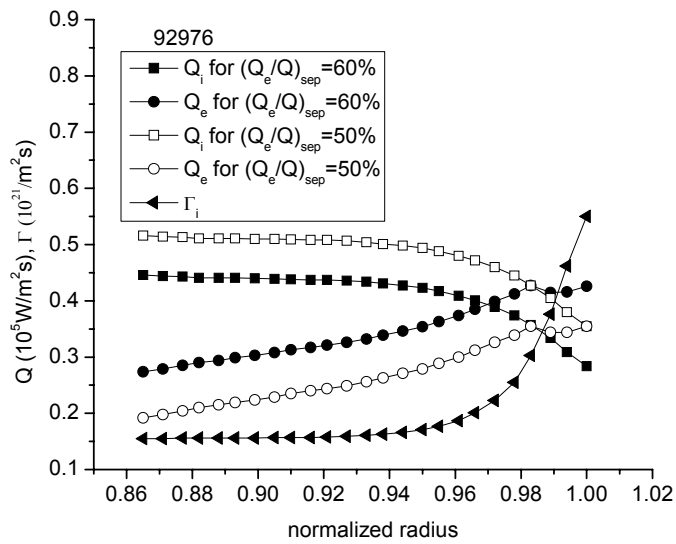


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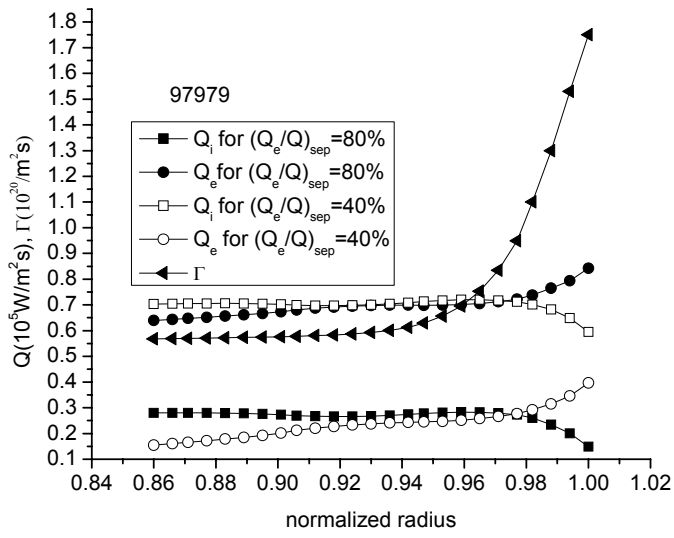


Fig. 6b

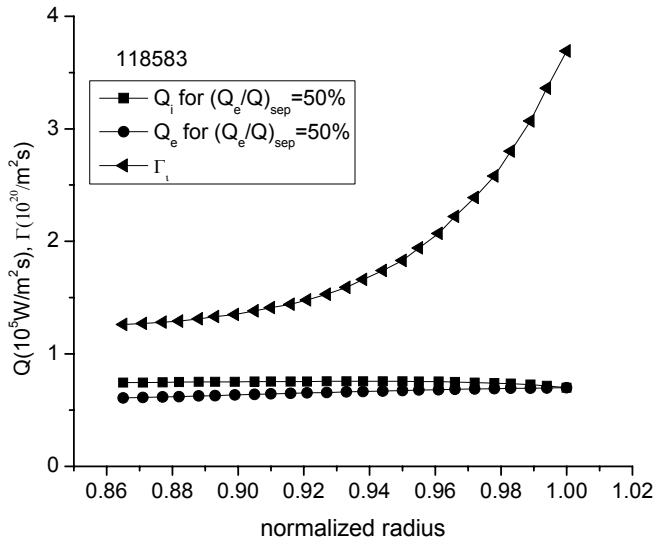


Fig. 6c

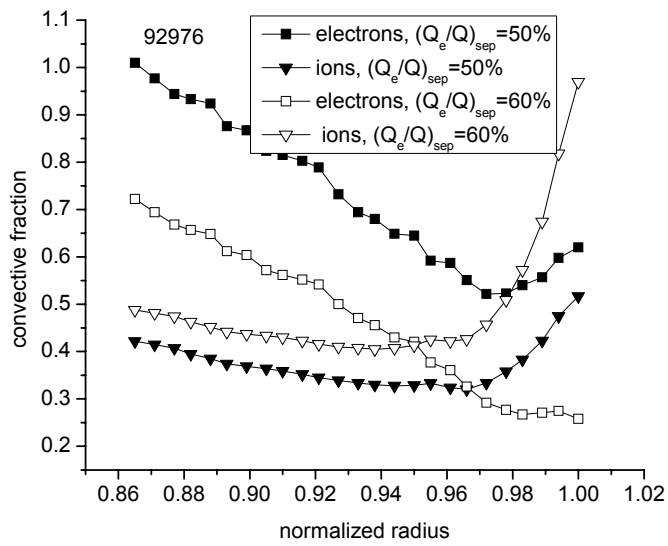


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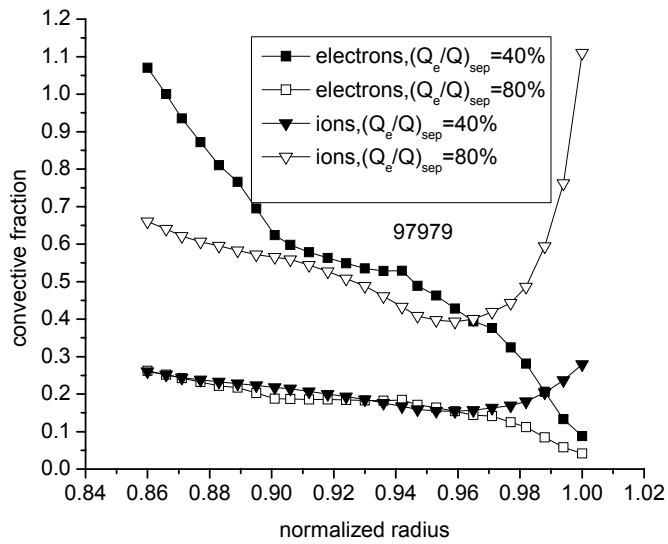


Fig. 7b

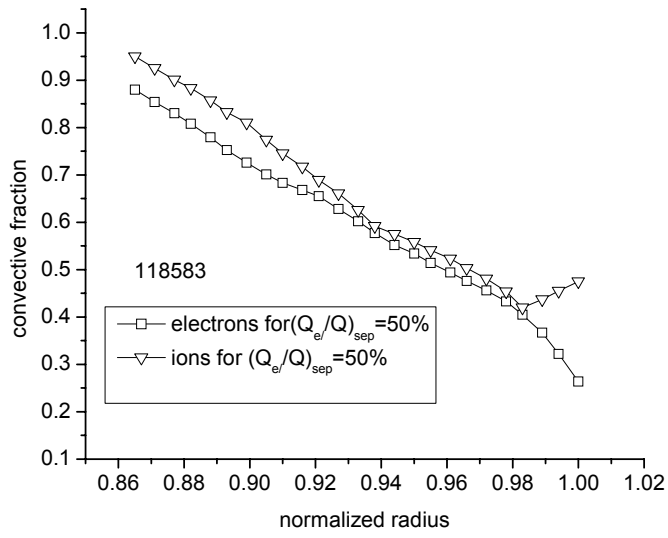


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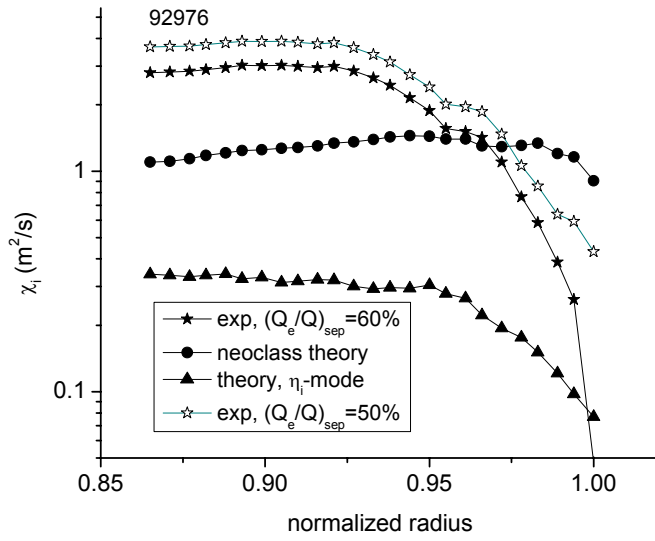


Fig. 8a

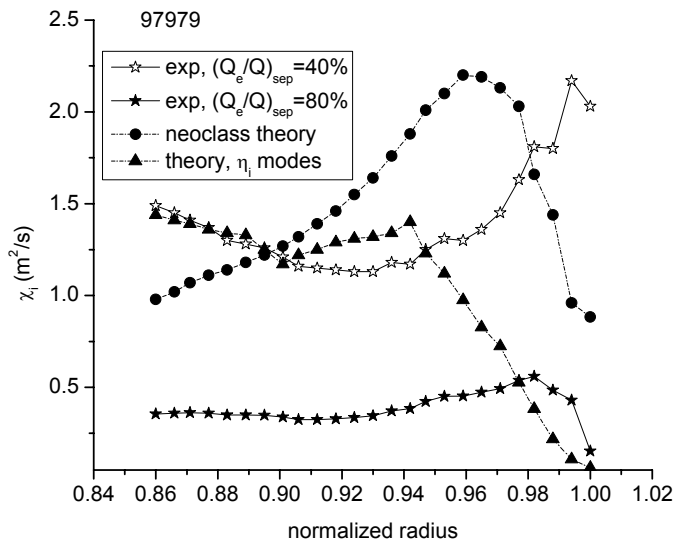


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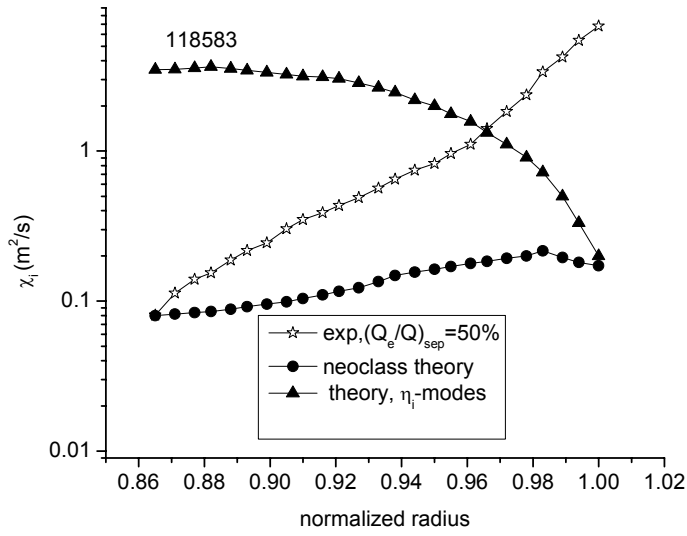


Fig. 8c

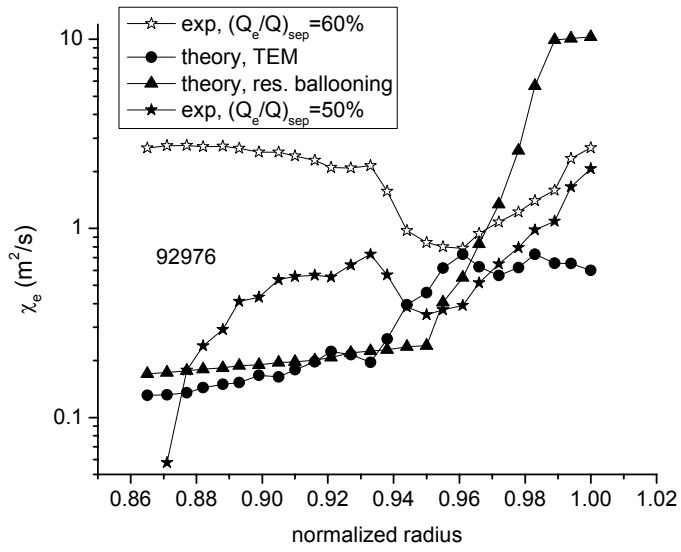


Fig. 9a

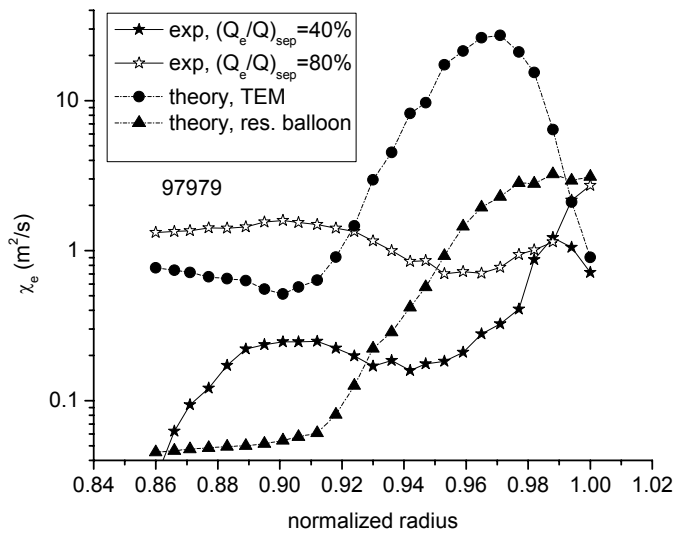


Fig. 9b

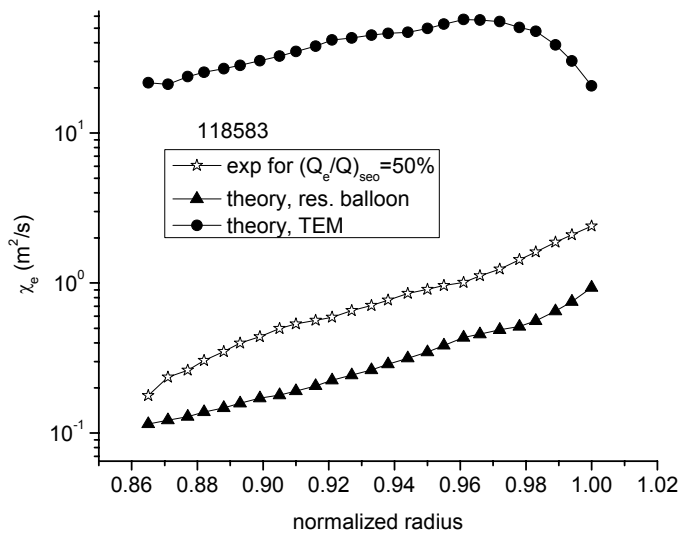


Fig. 9c