TRANSPORT OF PARTICLES AND IMPURITIES IN DIII–D DISCHARGES WITH INTERNAL REGIONS OF ENHANCED CONFINEMENT

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INTRODUCTION

- Understanding Particle Transport is essential to the successful design of a Tokamak fusion reactor

- It is likely that a fusion reactor will be designed to operate with regions of enhanced confinement. ("Enhanced confinement" means transport levels significantly lower than the usual L–mode or conventional ELMing H–mode transport)

- Here we address issues related to particle transport in Tokamak plasmas with regions of enhanced confinement

- Two main issues are:
  - Control of density profile shapes
  - Understanding of impurity accumulation and transport

THE PARTICLE FLUX EQUATION HAS LARGE CONDUCTIVE AND CONVECTIVE TERM

- Gas Puff and Pellet Injection Experiments show that,

$$\Gamma_j = -D_j \frac{\partial n_j}{\partial \rho} + V n_j$$

- Where the convective flux, Vn_j, is usually inward and non negligible

- V can have Neoclassical and Anomalous Components

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THE CONVECTIVE VELOCITY HAS TURBULENT AND NEOCLASSICAL COMPONENTS

Neoclassical

Ware Pinch $\propto E_{||}$

Thermal Screening ~ $-0.5\left(\frac{1}{T_i}\frac{\partial T_i}{\partial \rho}\right)$

Central Peaking ~ $z\left(\frac{1}{n}\frac{\partial n}{\partial \rho}\right)$

Turbulent

Various Derivations

$V_{Turb} \sim \frac{1}{T}\frac{\partial T}{\partial \rho}$

$V_{Turb} \sim -1\left(\frac{1}{q}\frac{\partial q}{\partial \rho}\right)$

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THE ELECTRON PARTICLE FLUX EQUATION

- For the purposes of this discussion, we can write the electron particle flux equation as,

$$\Gamma_e = -D_e\left[\frac{\partial n_e}{\partial \rho} - \frac{V_{turb}}{D} n_e\right] + V_{ware}\; n_e$$

- For electron particle flux in anomalously transporting plasmas, we use,

$$\frac{V_{turb}}{D} \approx -\xi\left[\frac{1}{qH}\frac{\partial}{\partial \rho} qH\right]$$

- H is a geometric term proportional to $dV/d\Phi$, where V is the plasma volume and Φ is the toroidal magnetic flux. ξ is an approximate constant which depends on the type of turbulent transport. This expression is based on the q dependence of DIII–D standard L–mode and H–mode density profiles, and is consistent with predictions of Isichenko et. al and Baker and Rosenbluth

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PLASMAS WITH HIGH TURBULENT TRANSPORT $n_e \propto (qH)^{-\xi}$

- In plasmas with high turbulent transport the ware pinch can be neglected

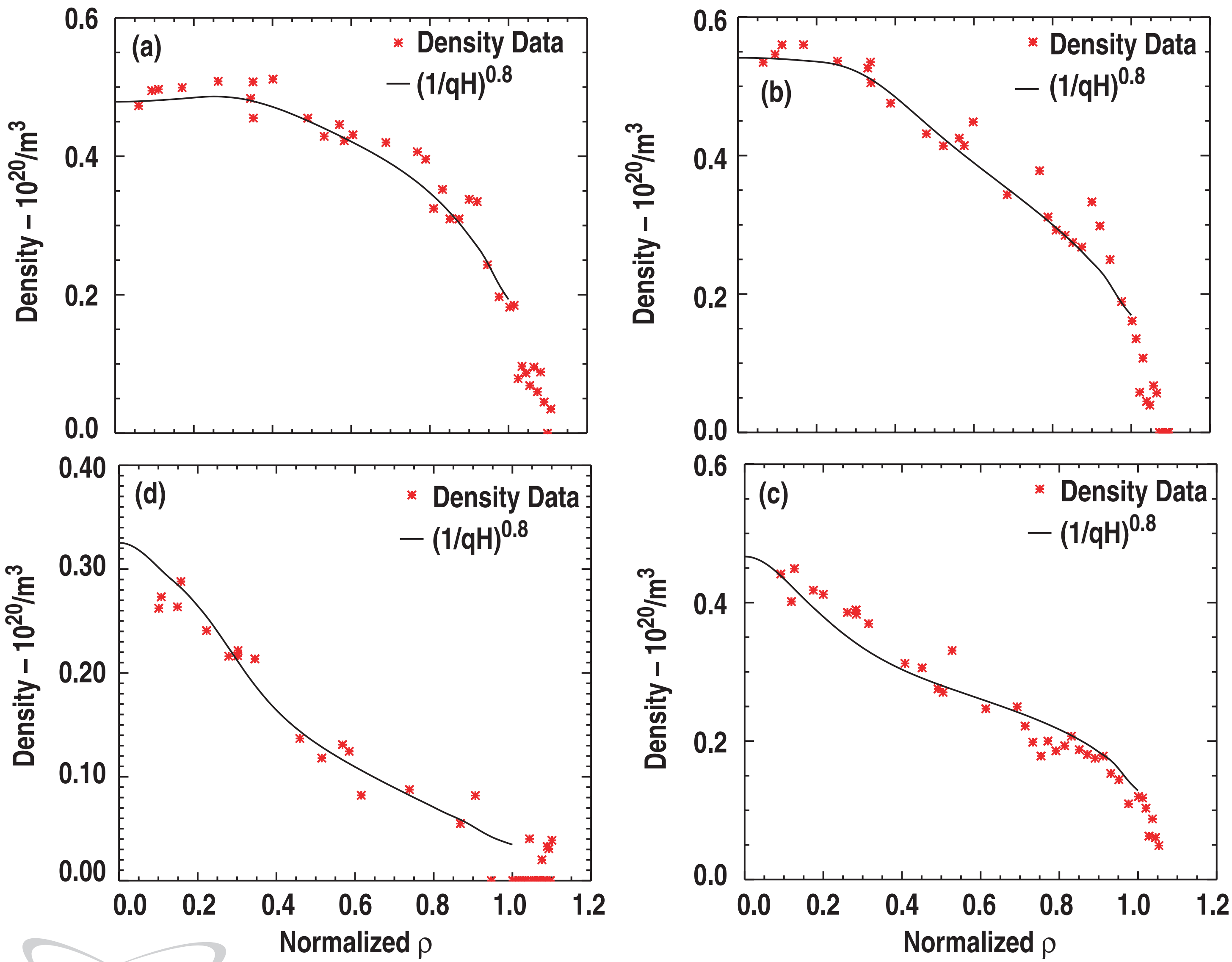
- Where $\Gamma_e \rightarrow 0$,

$$\frac{1}{n_e}\frac{\partial n_e}{\partial \rho} \approx \frac{V_{turb}}{D_e} \approx -\xi\left[\frac{1}{qH}\frac{\partial}{\partial \rho} qH\right]$$

or

$$n_e \propto (qH)^{-\xi}$$

IN HIGH TRANSPORT L–MODE PLASMAS $n_e \propto (qH)^{-0.8}$



The q profile is varied by ramping the plasma current up then down then up

The q profile is obtained from a 36 channel Motional Stark Effect diagnostic

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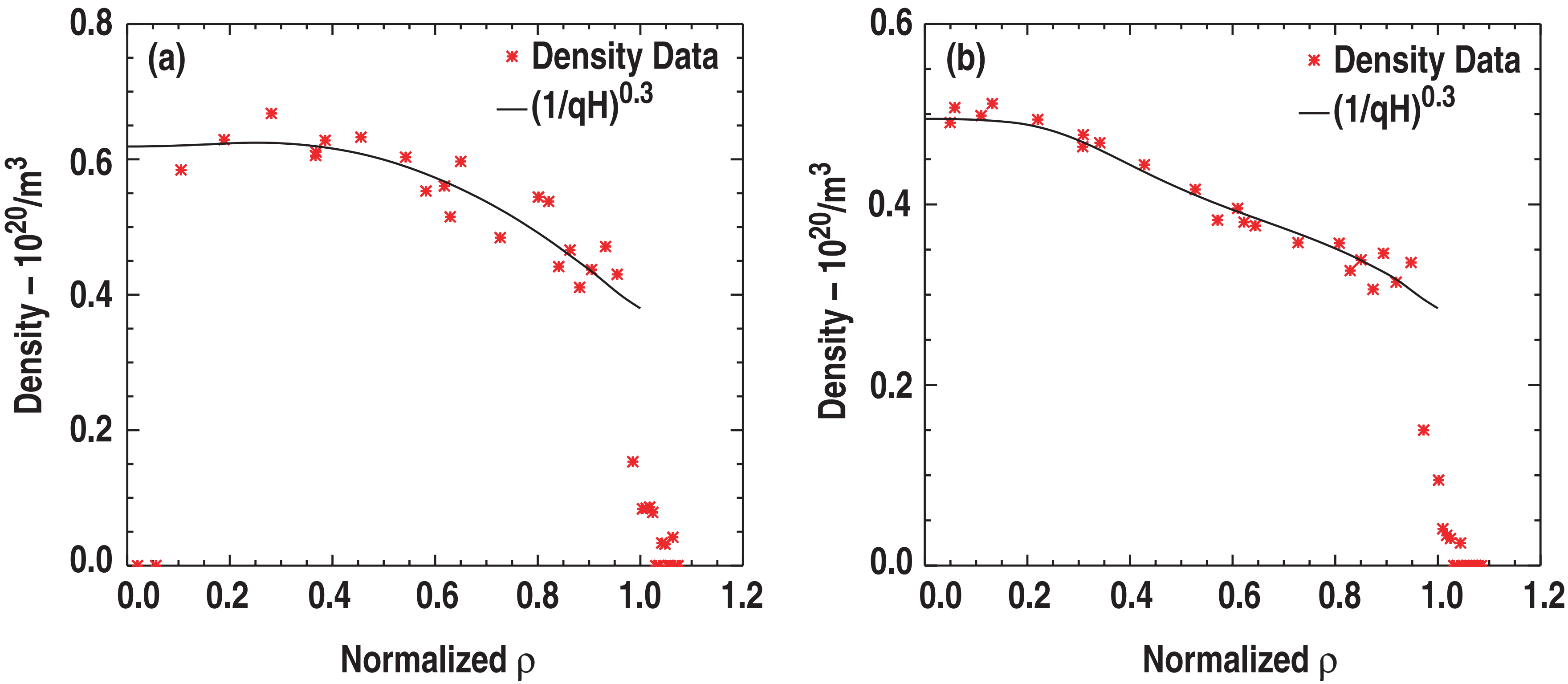
IN H–MODE PLASMAS WITH NO INTERNAL TRANSPORT BARRIER, $n_e \propto (qH)^{-0.3}$



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IMPURITY TRANSPORT

- The neoclassical part of the impurity particle flux can be written

$$\Gamma_z^{neo} = -D_{neo} \nabla n_z + n_z D_{neo} \left\{ \sum_i g_{j \to z} \frac{\nabla n_i}{n_j} + g_{T_i} \frac{\nabla T_i}{T_i} \right\}$$

- In steady state, with $\Gamma \to 0$, we obtain,

$$\frac{n_z(\rho)}{n_z(0)} = \left[\frac{n_D(\rho)}{n_D(0)} \right]^{g_{D \to Z}} \left[\frac{T_i(\rho)}{T_i(0)} \right]^{g_{T_i}}$$

- In the Banana Regime
  $g_{D \to z} \approx Z$ and $-1.0 < g_{T_i} < 0.0$

- Plasmas with steep density profiles and moderate ion temperature profiles will show central impurity accumulation

- Plasmas with flat density profiles and steep ion temperature profiles will show edge accumulation of impurities

TRANSPORT DATA IS CONSISTENT WITH A SIMPLE LINEAR COMBINATION OF BOTH TURBULENCE-DRIVEN AND COLLISION-DRIVEN (i.e., NEOCLASSICAL) TRANSPORT

Ansatz:

$$\underbrace{\Gamma_z = \Gamma_z^{turb} + \Gamma_z^{neoc}}$$

$$D_z = D_z^{turb} + D_z^{neoc}, \; V_z = V_z^{turb} + V_z^{neoc}$$

In most cases of interest, $D_z^{turb} \gg D_z^{neoc}$

- Hence, steady-state impurity profile shape can be much different from that expected from either turbulence-dominated or collision-dominated theories

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COMBINING TURBULENT AND NEOCLASSICAL

$$\frac{\nabla n_z}{n_z} = \frac{1}{1+\xi_I}\,\frac{\nabla n_i}{n_i} + \frac{\xi_I}{1+\xi_I}\left(Z\,\frac{\nabla n_i}{n_i} + g_{Ti}\,\frac{\nabla T_i}{T_i}\right)$$

with $\xi_I = D_{neo}/D_{turb}$

- Result is less impurity accumulation than is predicted by neoclassical transport alone

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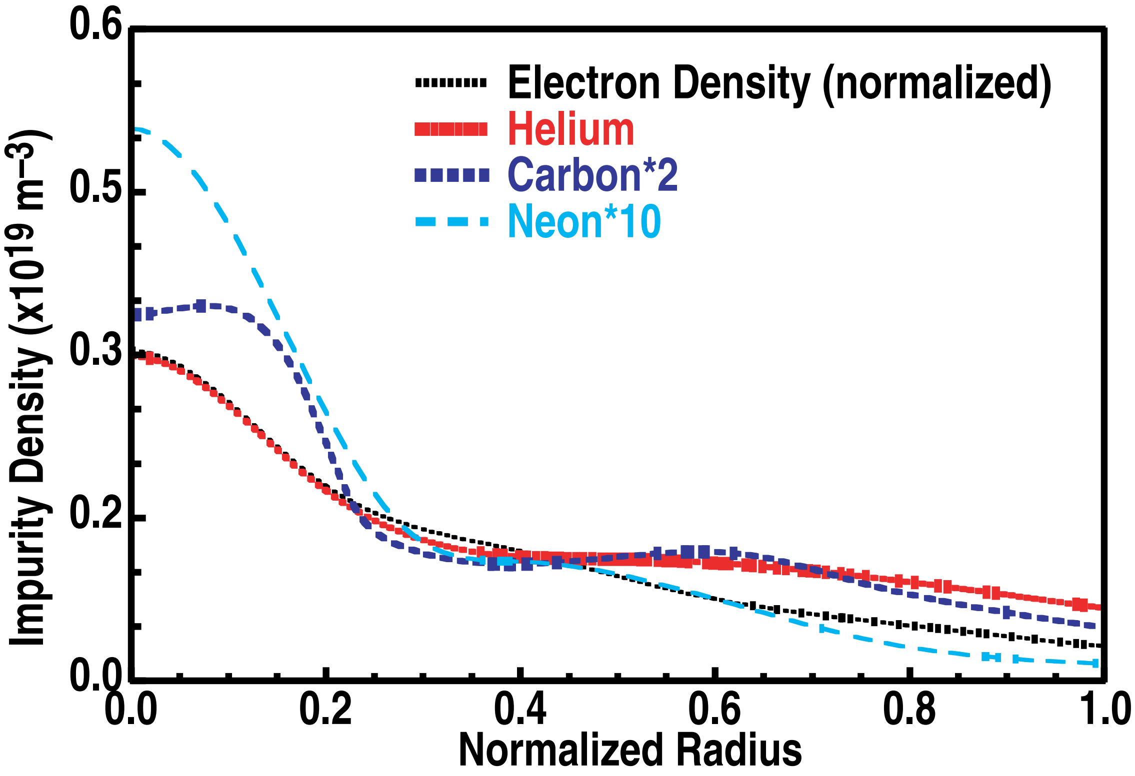
DISCHARGES WITH ITB AND PEAKED DENSITY PROFILES SHOW CENTRAL IMPURITY ACCUMULATION

- Experimentally measured impurity accumulation is weaker than neoclassical and agrees with combined result



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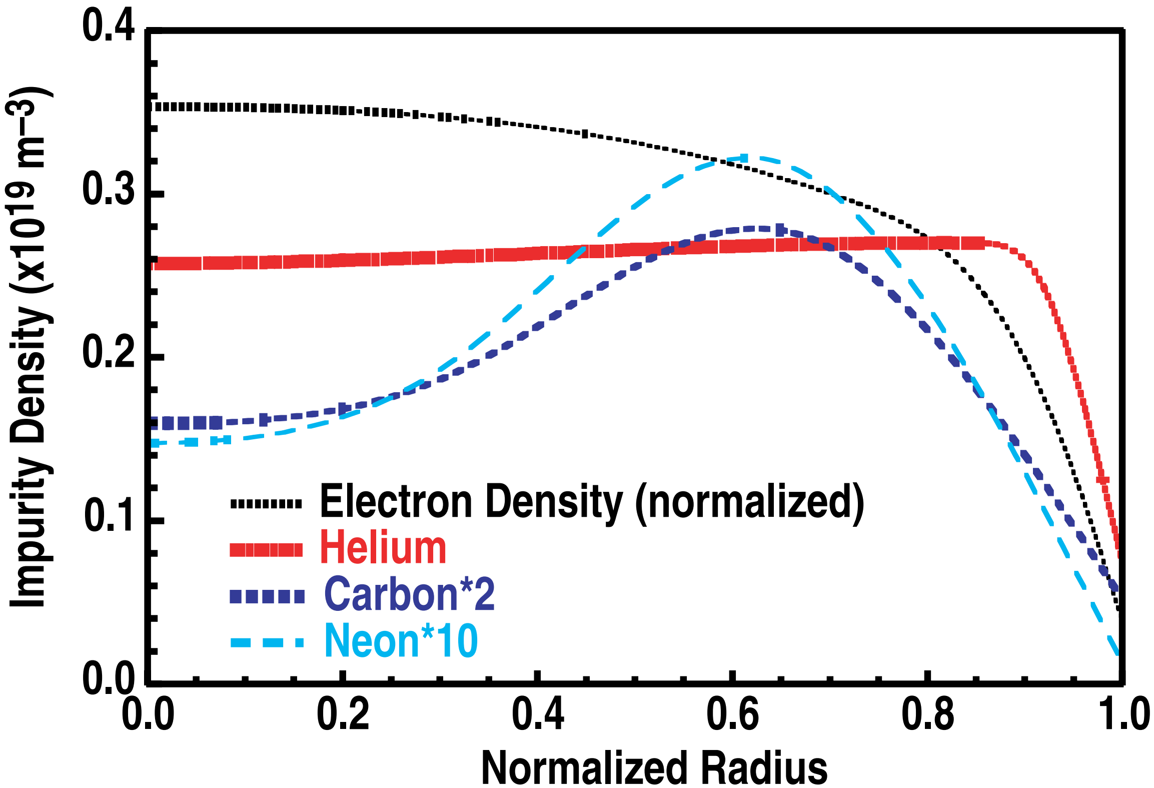
VH–MODE DISCHARGES SHOW EDGE ACCUMULATION OF IMPURITIES

- In VH–mode plasmas with flat density profiles and peaked ion temperature profiles, the medium weight impurities accumulate near the edge



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EXPRESSIONS FOR THE PARTICLE DIFFUSION COEFFICIENT

- The electron particle flux in the core of the plasma can be calculated from the sources. Then the diffusion coefficient can be calculated

- If the Ware pinch term is neglected we obtain,

$$D_{wow} = \frac{\Gamma_e / n_e}{-\frac{1}{n_e}\frac{\partial n_e}{\partial \rho} - \xi \frac{1}{qH}\frac{\partial qH}{\partial \rho}}$$

(wow ~ WithOut Ware pinch)

- Inclusion of the Ware pinch yields, $$D_e = \frac{\Gamma_e / n_e - V_{ware}}{-\frac{1}{n_e}\frac{\partial n_e}{\partial \rho} - \xi \frac{1}{qH}\frac{\partial qH}{\partial \rho}}$$

  - In regions of anomalous transport, D_e is not well defined since the denominator is the difference of two large terms
  - In regions of enhanced confinmemnt, the two terms in the denominator no longer cancel and D_e is well defined

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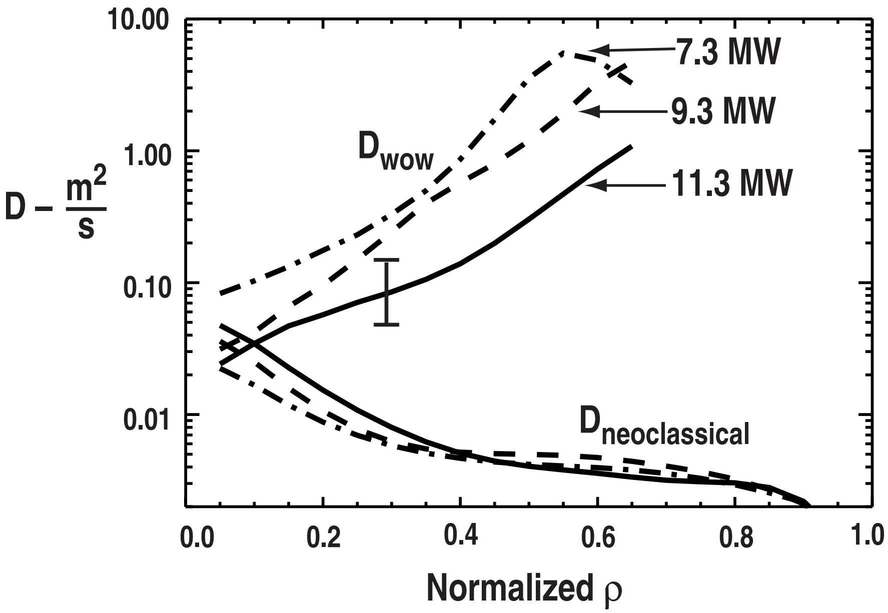
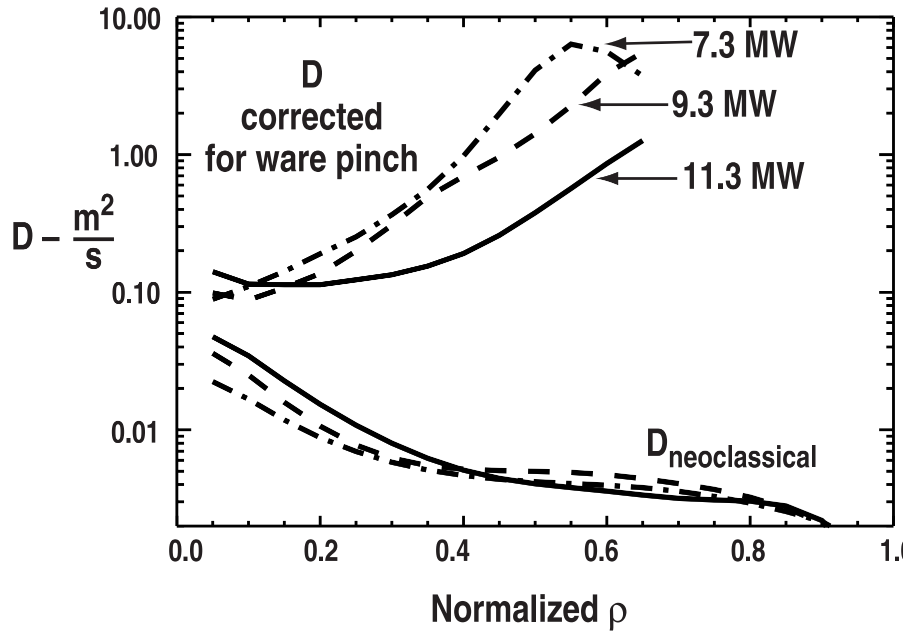
REGION OF ENHANCED CONFINEMENT FOR ρ < 0.5 PARTICLE DIFFUSIVITIES WITH AND WITHOUT CORRECTION FOR WARE PINCH

- Data shown is from TRANSP analysis for 3 ITB plasmas with different input power



Without Correction for Ware Pinch



With Correction for Ware Pinch

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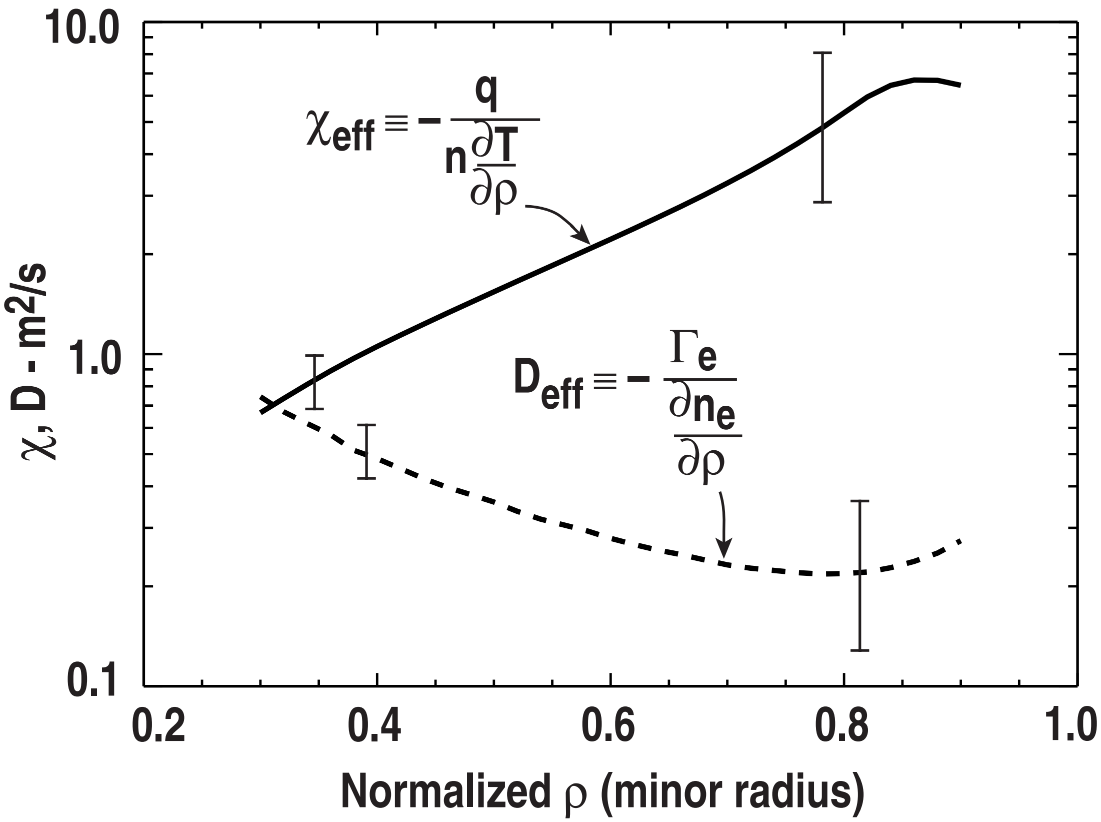
RELATION BETWEEN PARTICLE AND ENERGY TRANSPORT

- The particle flux and the energy heat can have widely different dependence on plasma parameters



$q \equiv q_i + q_e$

$T \equiv T_i + T_e$

$n \equiv \frac{n_i + n_i}{2}$

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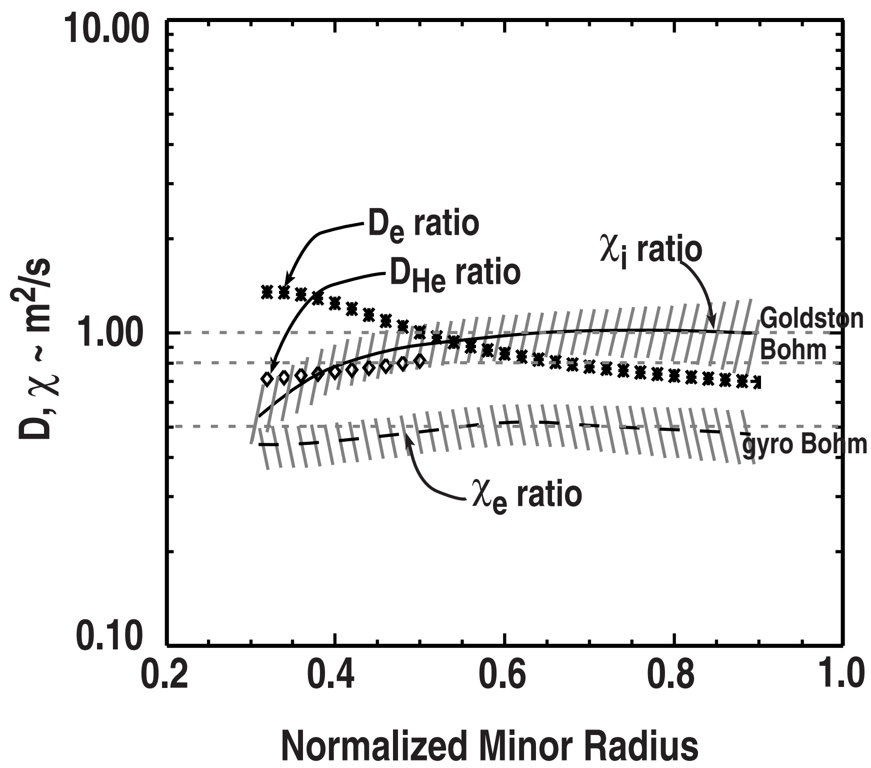
DIMENSIONLESS SCALING OF PARTICLE DIFFUSIVITY

- Direct Measurement of D (and V) show that D ~ χ_{eff} or χ_i
  - — The difference in the behavior between heat flux and particle flux is due to the convective part of the flux

- Dimensionless scaling experiments show that for L–mode plasmas D_{He} scales as Bohm like For H–mode plasmas D_{He} scales like gyro-Bohm which is like χ_i, χ_{eff} or χ_e D_e scales between Bohm and Goldston. Both D_{He} and D_e scale close to χ_i



L–mode

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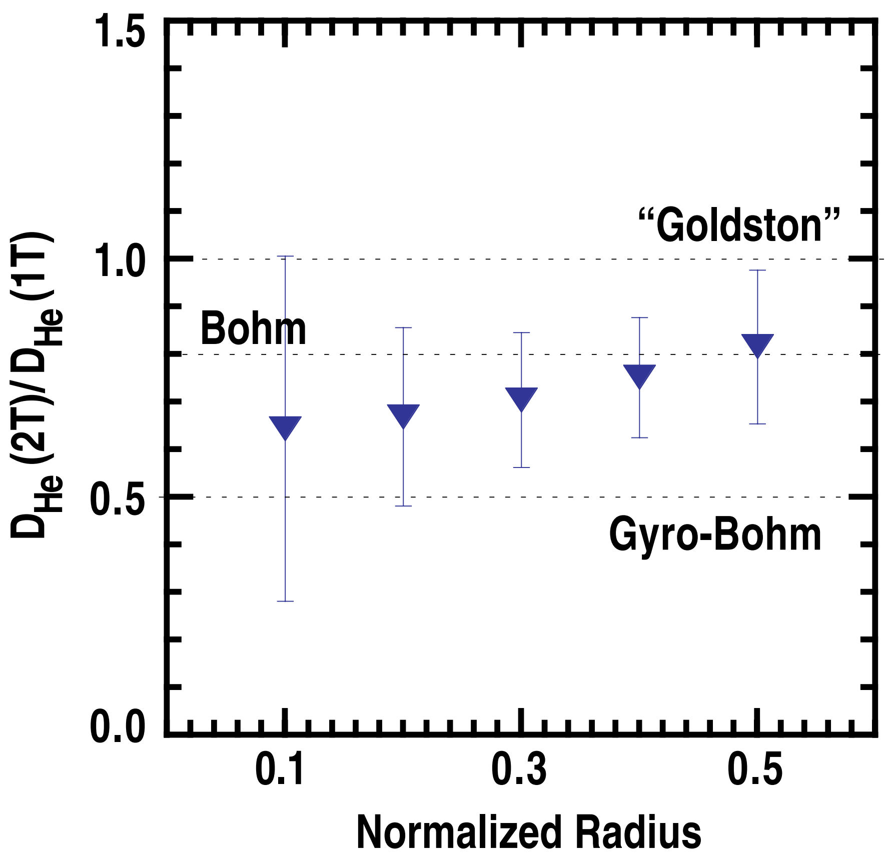
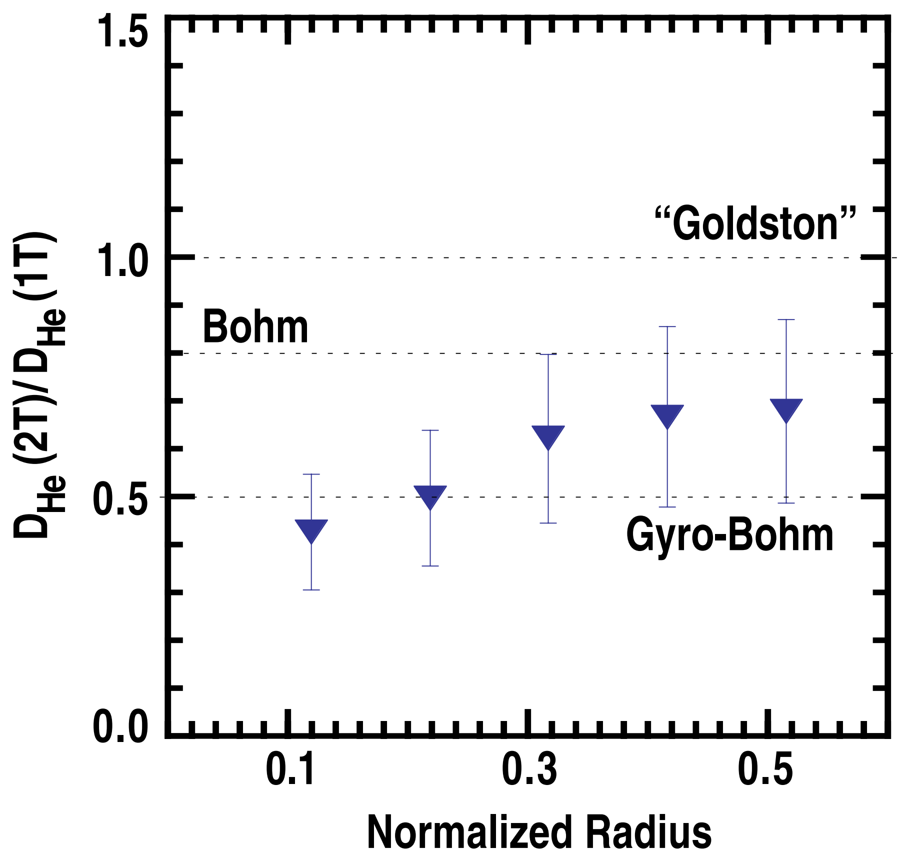
DIMENSIONLESS SCALING AT PARTICLE DIFFUSIVITY



L–mode



H–mode

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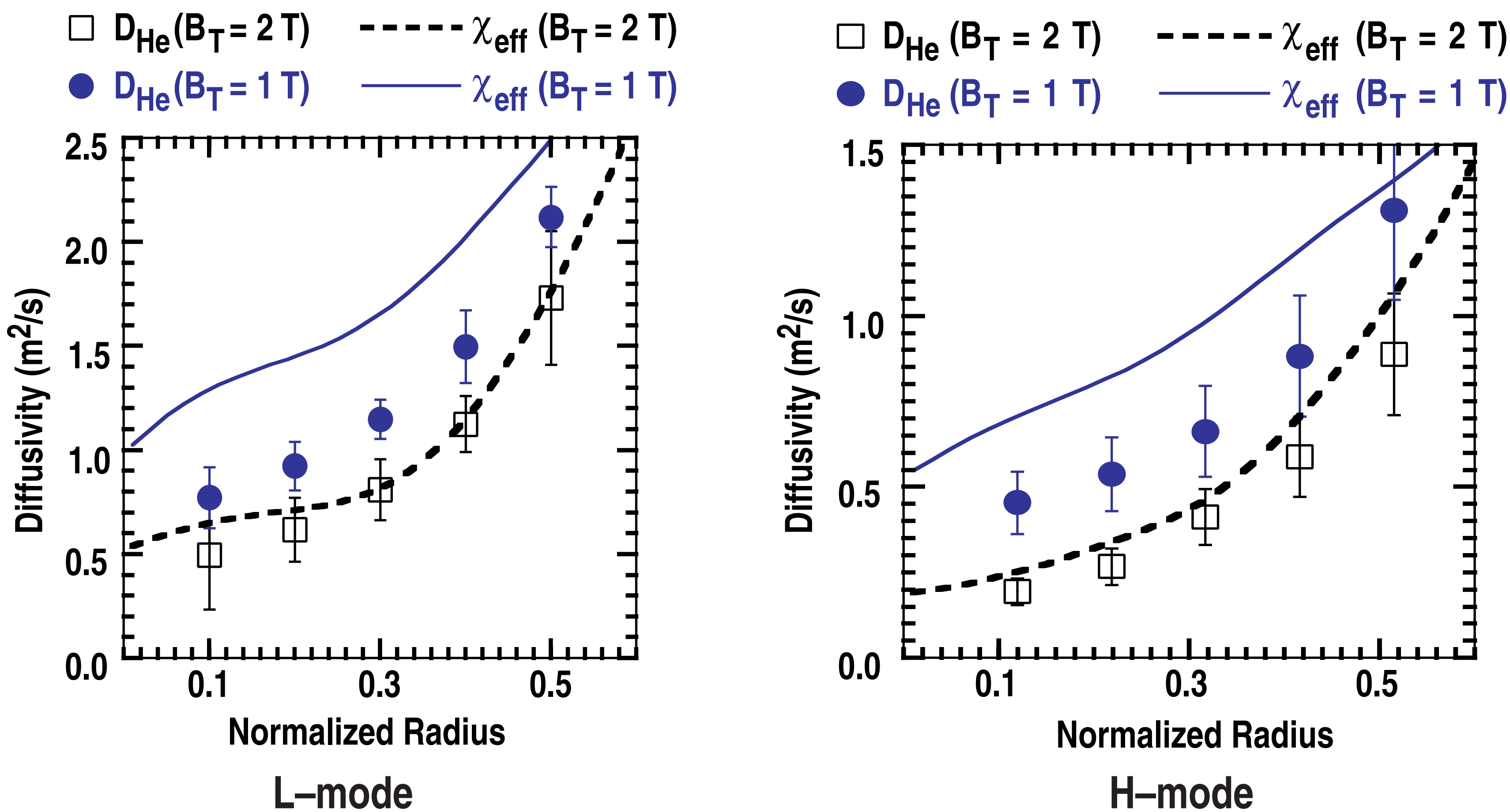
GAS PUFF MEASUREMENTS SHOW THAT D_{He} HAS SIMILAR MAGNITUDE AND RADIAL DEPENDENCE AS χ_{eff}



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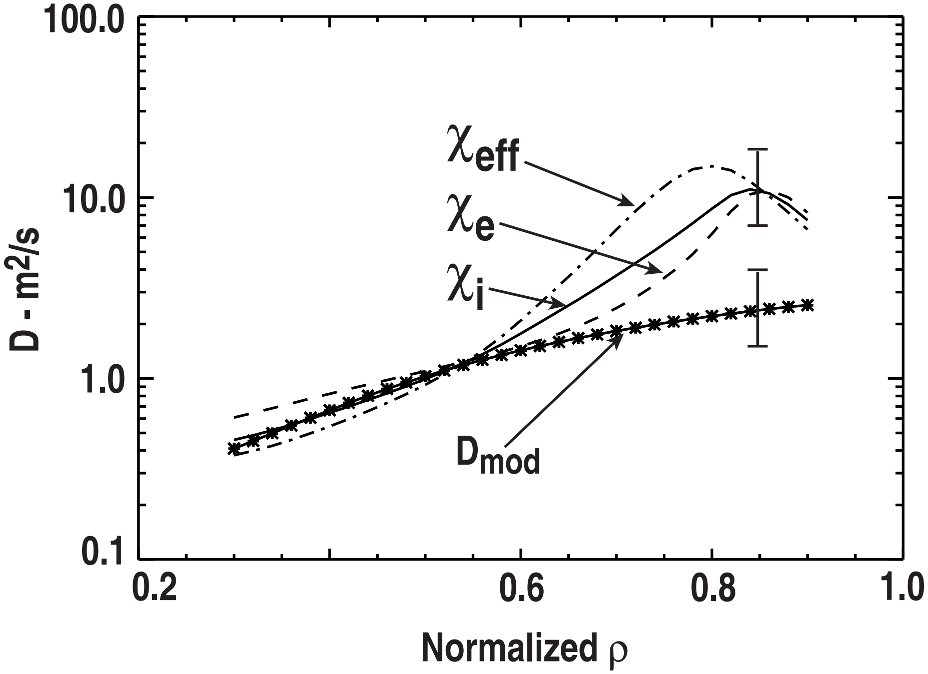
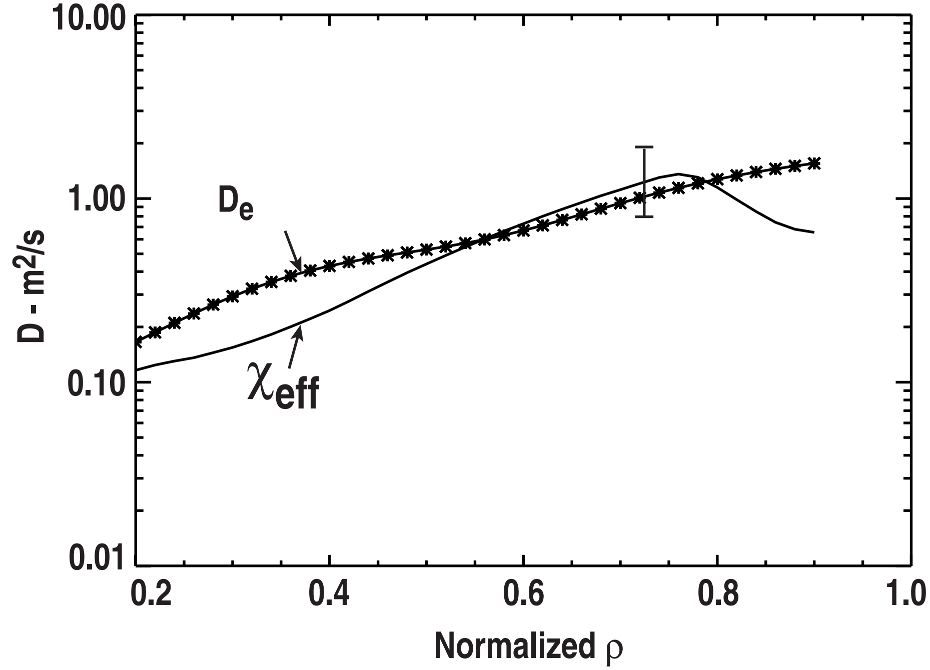
GAS PUFF MEASUREMENTS SHOW THAT D_e HAS SIMILAR MAGNITUDE AND RADIAL DEPENDENCE AS χ_{eff}



L–mode



H–mode

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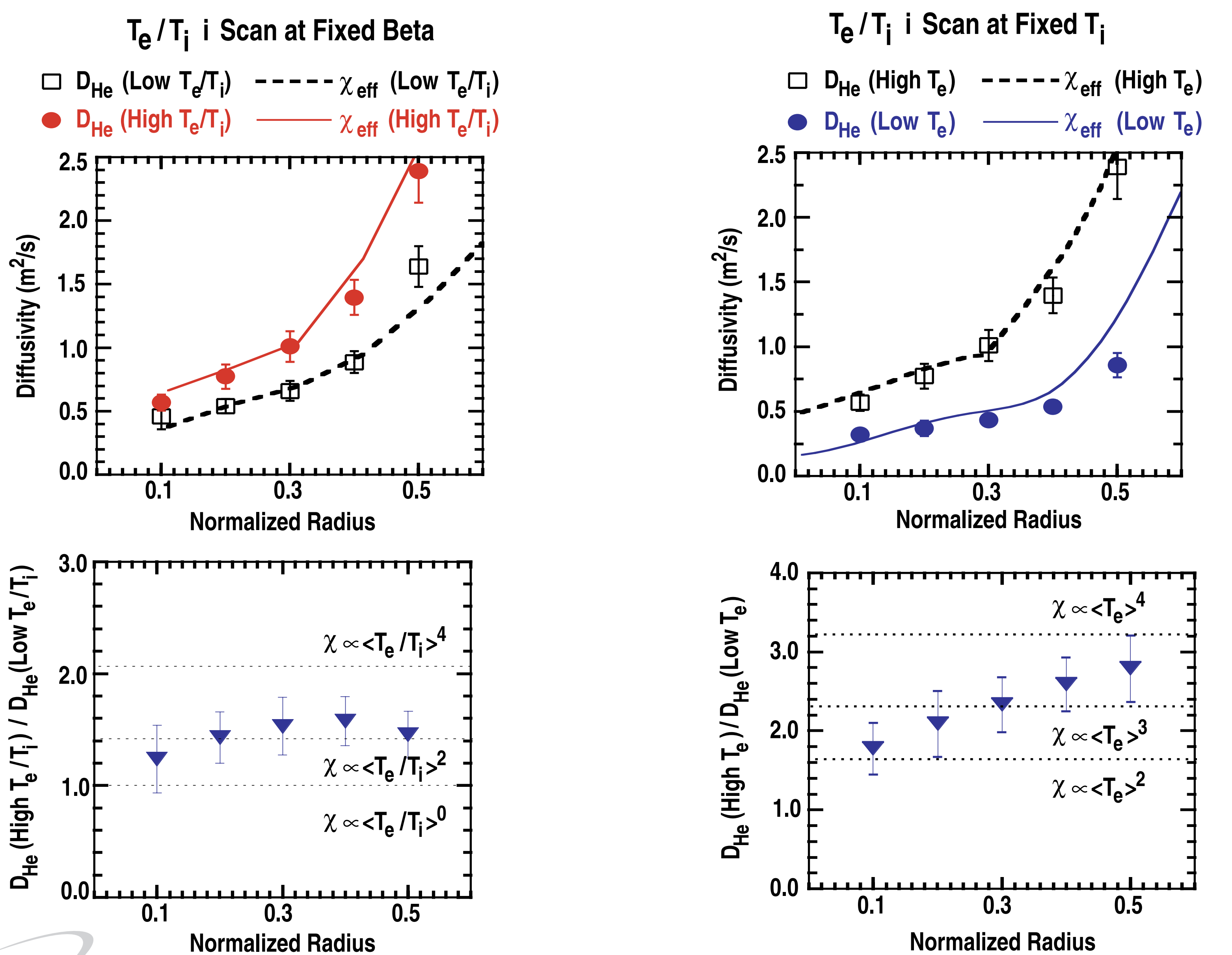
STRONG T_e/T_i DEPENDENCE IS OBSERVED FOR BOTH ENERGY AND HELIUM TRANSPORT IN H–MODE PLASMAS



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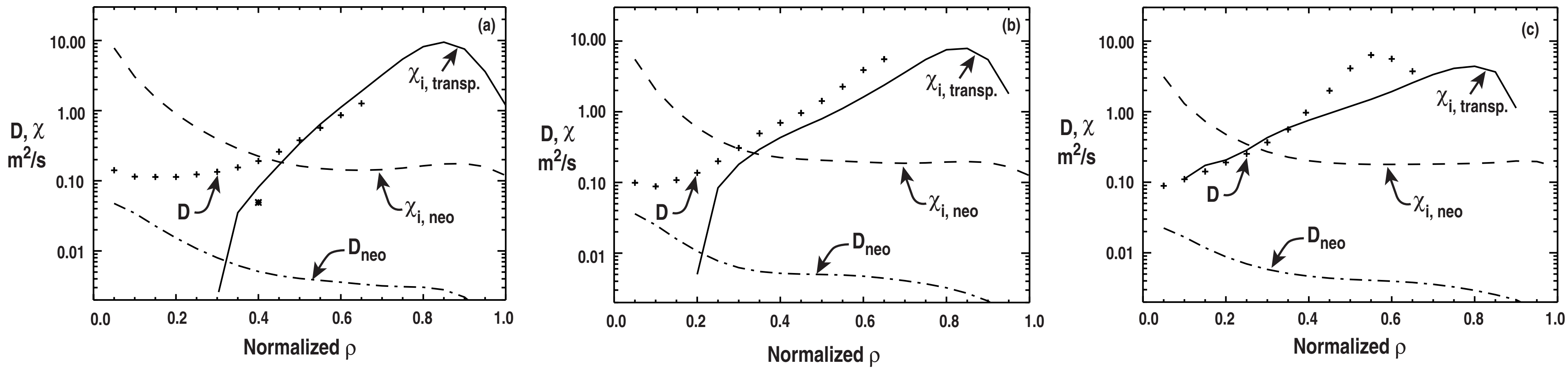
COMPARISON BETWEEN D_e AND χ_i FOR ENHANCED CONFINEMENT DISCHARGES

- In DIII–D NCS plasmas with ITBs, D_e is more closely related to χ_i than χ_e
  For many DIII–D plasmas with ITBs, $\chi_i \Rightarrow \chi_{neoclassical}$, while χ_e remains high.
  In these plasmas, $D_e \Rightarrow D_{neoclassical}$

Transport analysis for 3 ITB shot with different NBI



11.3 MW   9.3 MW   7.3 MW

SUMMARY

- **Turbulent Transport (L–mode, conventional ELMing H–mode)**
  - $n_e \sim (qH)^{-\xi}$
  - D_{He} and $D_e \sim \chi_{eff}$
  - No central accumulation of light or medium weight impurities
  - In L–mode, D_e and D_{He} scale in a Bohm manner
  - In H–mode, D_{He} scales in a gyro-Bohm manner
  - D_{He} increases strongly with increasing T_e/T_i in H–mode

- **Enhanced Confinement (ITBs or VH–mode)**
  - D_e greatly reduced in regions where χ_i ~ neoclassical
  - No apparent accumulation of H_e with respect to deuterium
  - Central accumulation of C and Ne in NCS plasmas with ITBs
    - ★ Major exception: Recent DIII–D counter injection NCS/ITB discharges with an ELM free edge show no apparent central impurity accumulation (QH–mode)
  - Promote Edge accumulation of C and Ne in VH–mode with flat density profile