Introduction*

- Ultimately, the degree of contamination due to low-Z impurities in a fusion-grade plasma is determined by two factors: 1) source rates (either sputtered or injected) and 2) impurity transport.
- The acceptable source rate is strongly dependent on the details of the transport of impurities from the edge to the core plasma.

- Significant progress has been made in recent years on characterizing impurity transport in a variety of confinement regimes in DIII-D
- Goal of this Work:

  1) Develop and test a model for impurity transport that describes observation in various confinement regimes.

  2) Use this model to project what effect impurity transport will have on future tokamaks and develop criteria for acceptable impurity source rates in various regimes

Low-Z Impurity Transport in DIII–D — Observations and Implications

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Evidence for Neoclassical Impurity Transport

- Neoclassical transport effects have been observed in both NCS and VH-mode plasmas

NEOCLASSICAL IMPURITY FLUX (neglecting electrons and other impurites)

$$\Gamma_z^{neoc} = -D_{neoc}\nabla n_z + n_z D_{neoc}\left\{ g_{T_i}\frac{\nabla T_i}{T_i} + g_{D\rightarrow z}\frac{\nabla n_D}{n_D}\right\}$$

In steady-state, this reduces to

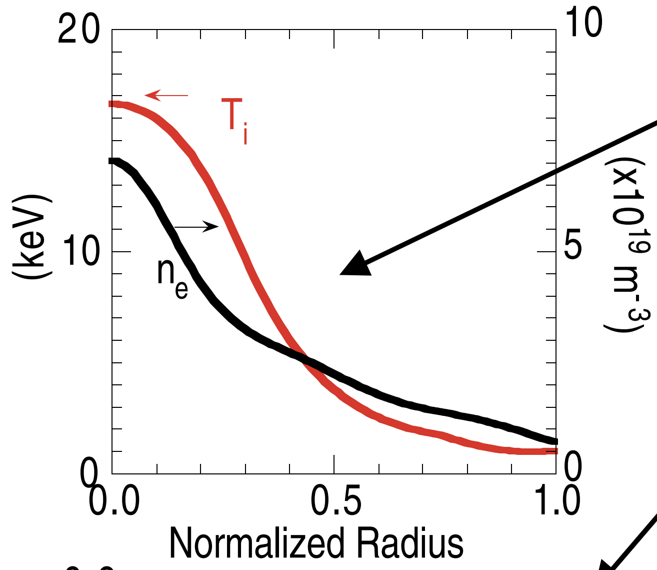
$$\frac{\nabla n_z}{n_z} = \left(\frac{\nabla n_D}{n_D}\right)^{g_{D\rightarrow Z}}\left(\frac{\nabla T_i}{T_i}\right)^{g_{T_i}}$$

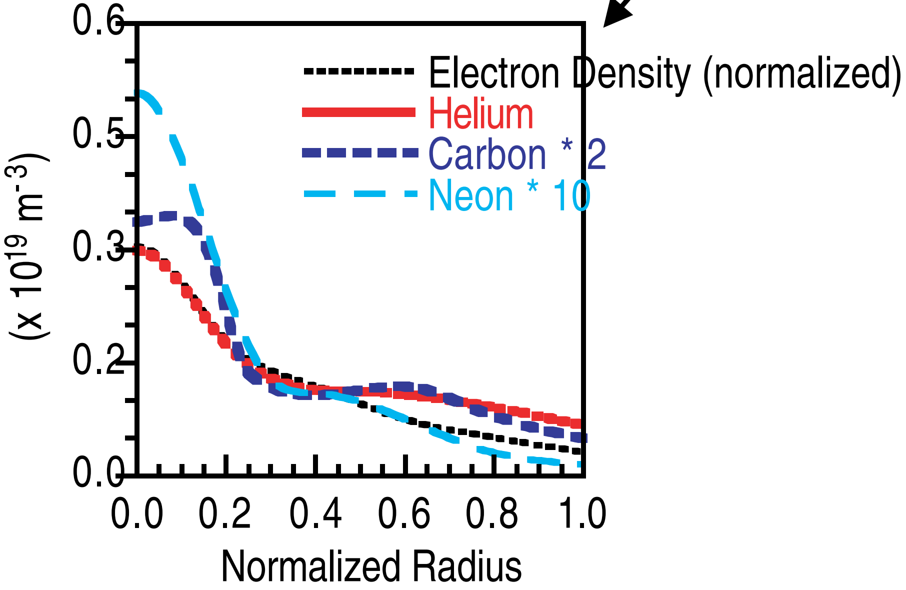
Observations in DIII-D

- In NCS plasmas with peaked density profiles, accumulation of low-Z impurities is observed.
- In VH-mode plasmas with flat density profiles, impurity screening by the ion temperature gradient is observed.

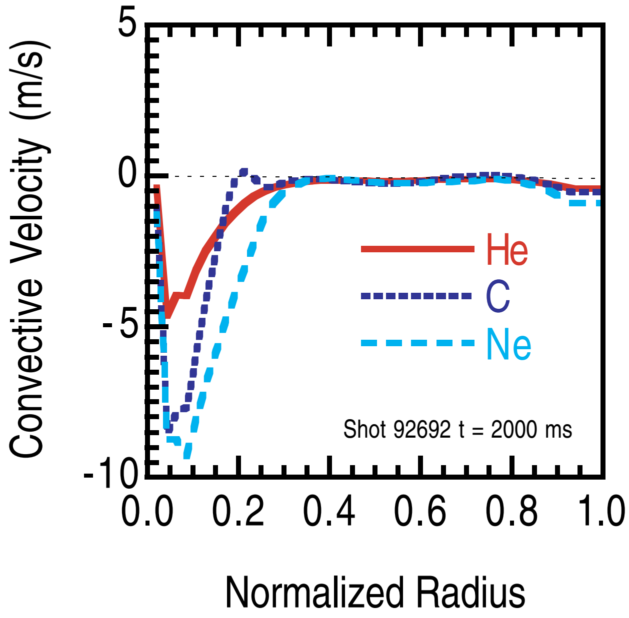
Impurity Accumulation Has Been Observed in NCS L-mode Discharges with Peaked Density Profiles

- Peaked density and ion temperature profiles lead to impurity accumulation of low Z impurities.



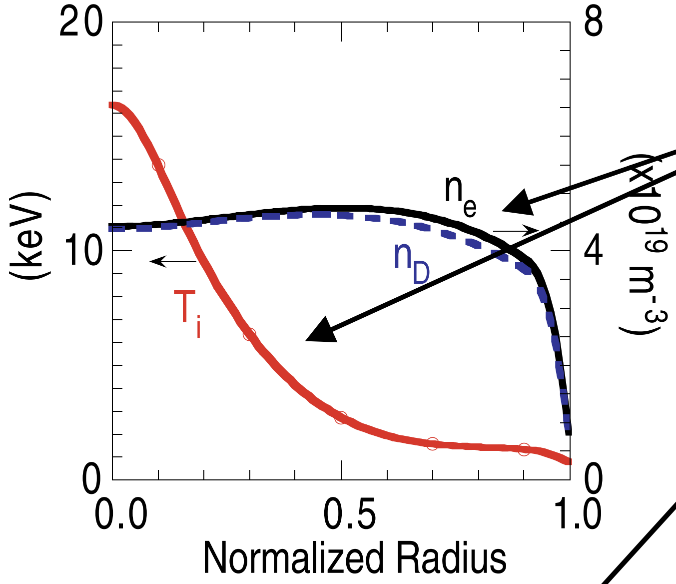


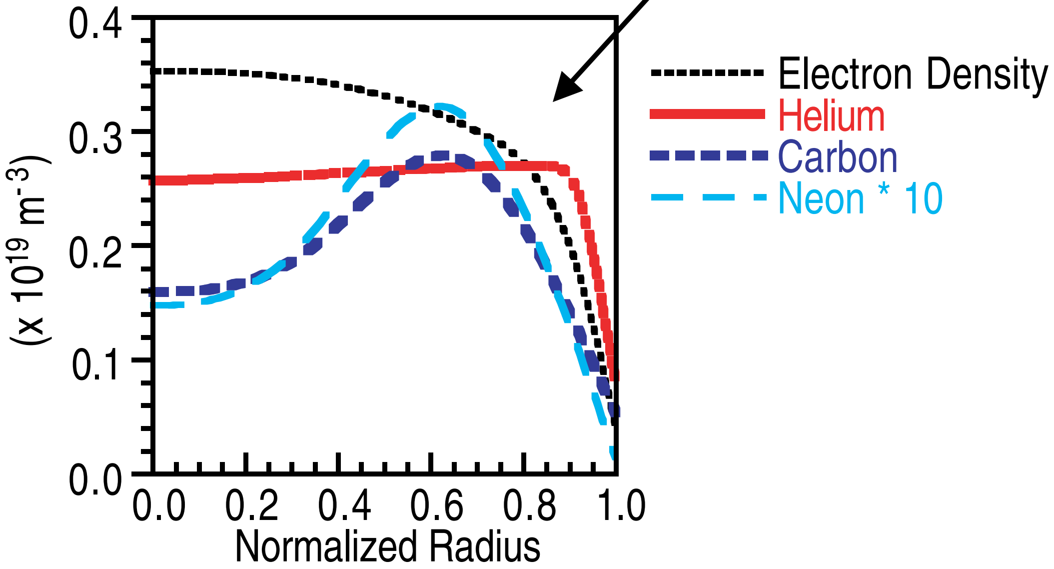
- Strong Inward Impurity Convection Predicted by Neoclassical Theory



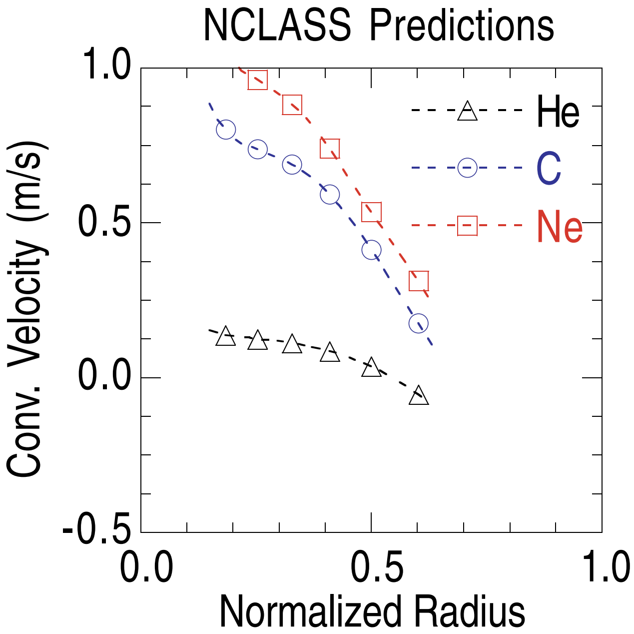
Hollow Impurity Density Profiles are Observed in VH-mode Plasmas - Consistent with Temperature Screening Predictions

- **Flat Density Profile and Peaked Ion Temperature Profile Lead to Hollow Carbon and Neon Density Profiles**





- **Hollow Profiles Consistent with Neoclassical Predictions**



Evidence for Turbulence-Driven Impurity Transport

- In plasmas with large levels of turbulence present (L-mode and H-mode), it is generally observed that:

  a) $D_Z \sim \chi_{eff}$

  ==> Not predicted by neoclassical theory. Suggestive of a strong link between energy and particle transport.

  b) In L-mode and H-mode, all impurity profiles have similar shapes as the electron density profile and impurity transport coefficients are comparable over a moderate range in impurity charge (helium and neon).

  ==> If electrostatic turbulence dominates transport, then this result is expected since the ExB drift associated with the fluctuating electric field is not dependent on charge or mass.

- Non-dimensional scaling studies (see below) have shown that:

  a) D_Z scales in a gyro-Bohm manner in H-mode

  ==> Indicates that the characteristic scale length for transport is on the order of a gyroradius, consistent with what is expected from turbulent transport theories.

  b) D_Z has a strong dependence on plasma electron temperature ($\sim T_e^3$)

  ==> Much stronger dependence than predicted by neoclassical and consistent with ion temperature gradient turbulence predictions.

Non-dimensional Scaling Studies

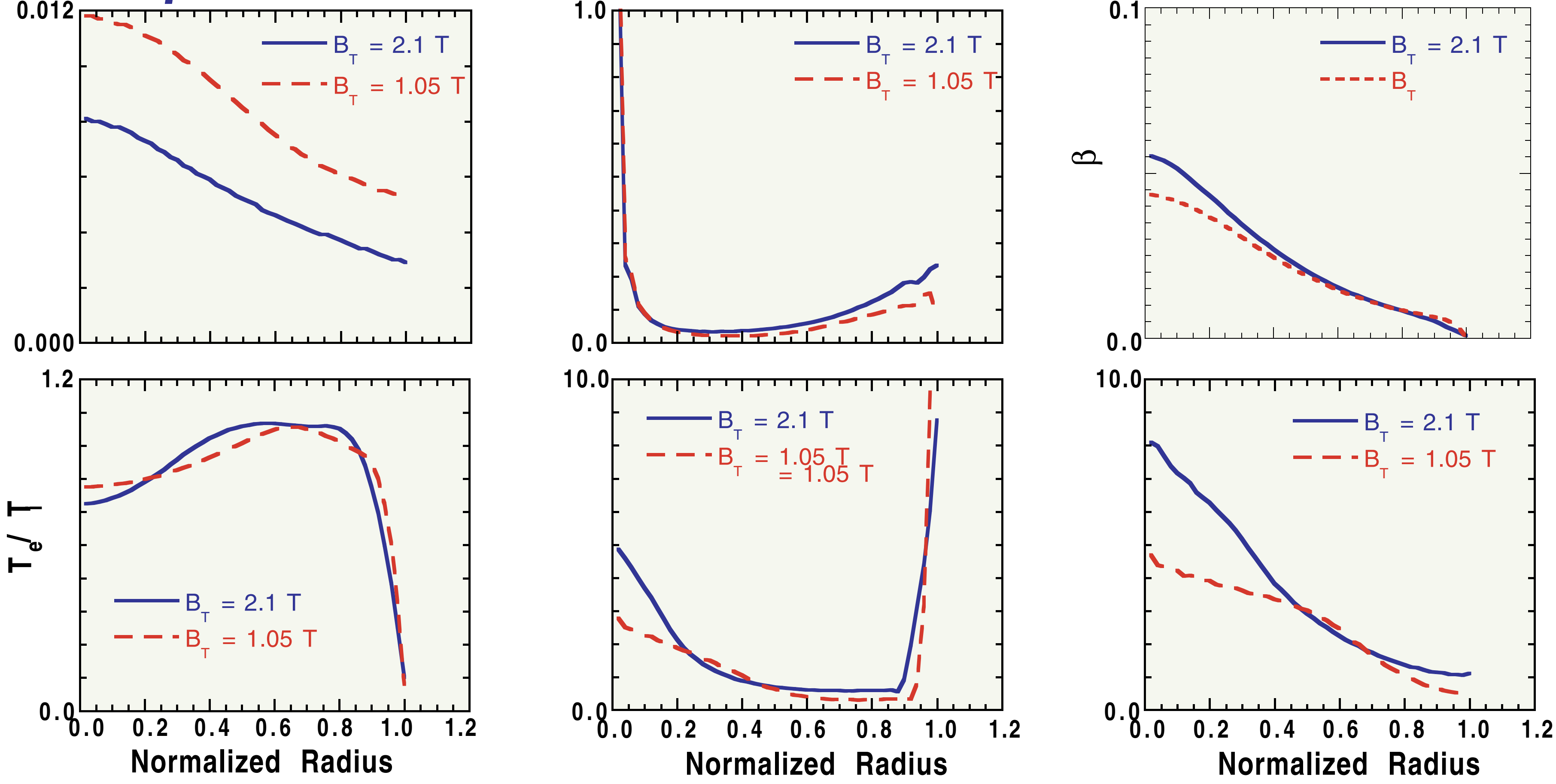
Premise: In a system governed entirely by plasma physics, the particle and energy diffusivity can be written in the form:

$$D = D_B (\rho_*)^{\alpha_1} F(\beta, \nu_*, q, T_e / T_i, R / a, \kappa, \ldots)$$

$$\chi = \chi_B (\rho_*)^{\alpha_2} F(\beta, \nu_*, q, T_e / T_i, R / a, \kappa, \ldots)$$

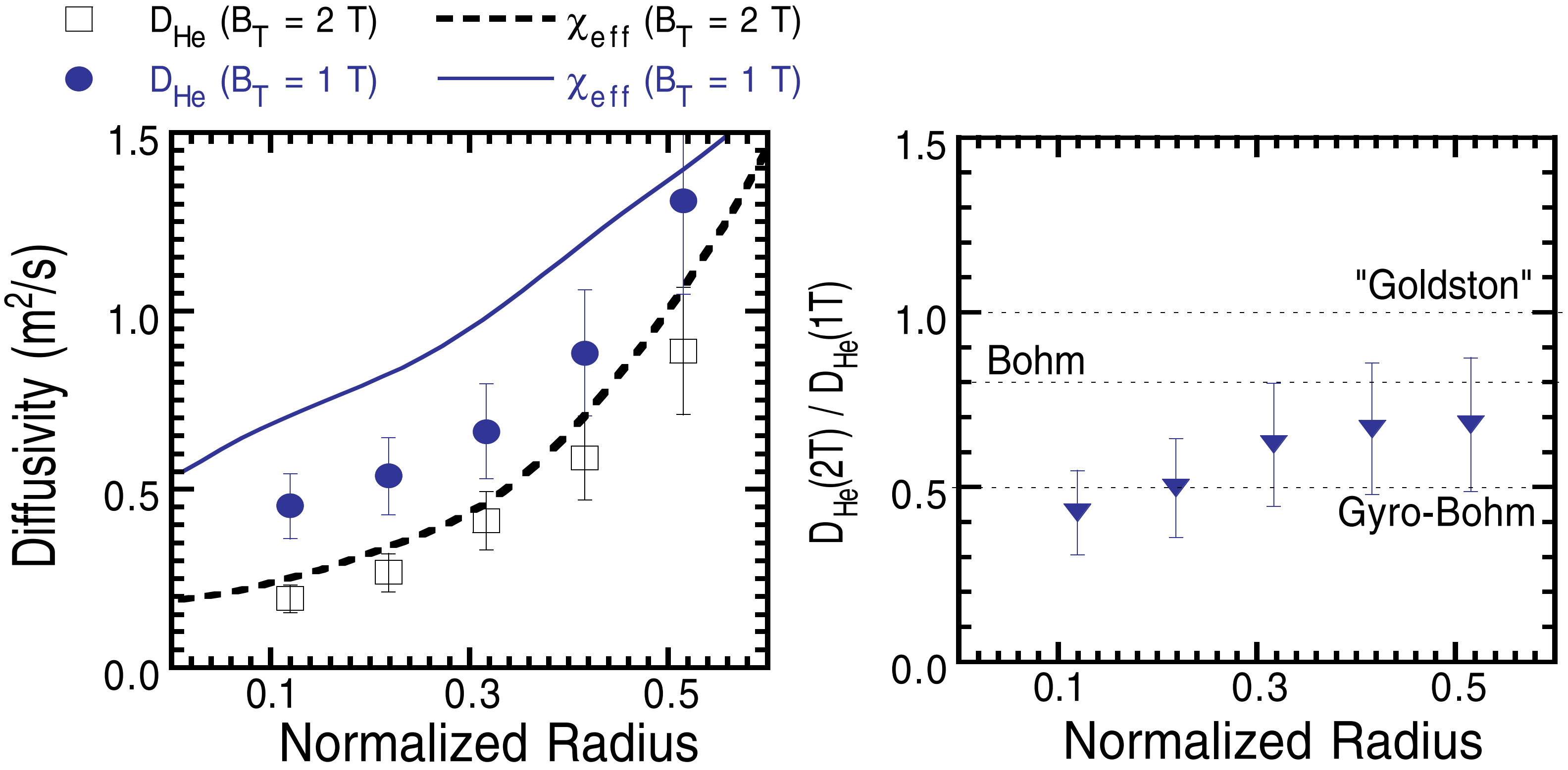
Experimentally, one can determine the dependence on each nondimensional parameter by matching all the other parameters and then measuring the differences in transport.

Example: ρ^* Scan



Helium Transport Scales in a Gyro-Bohm-Like Manner in H-mode Plasmas

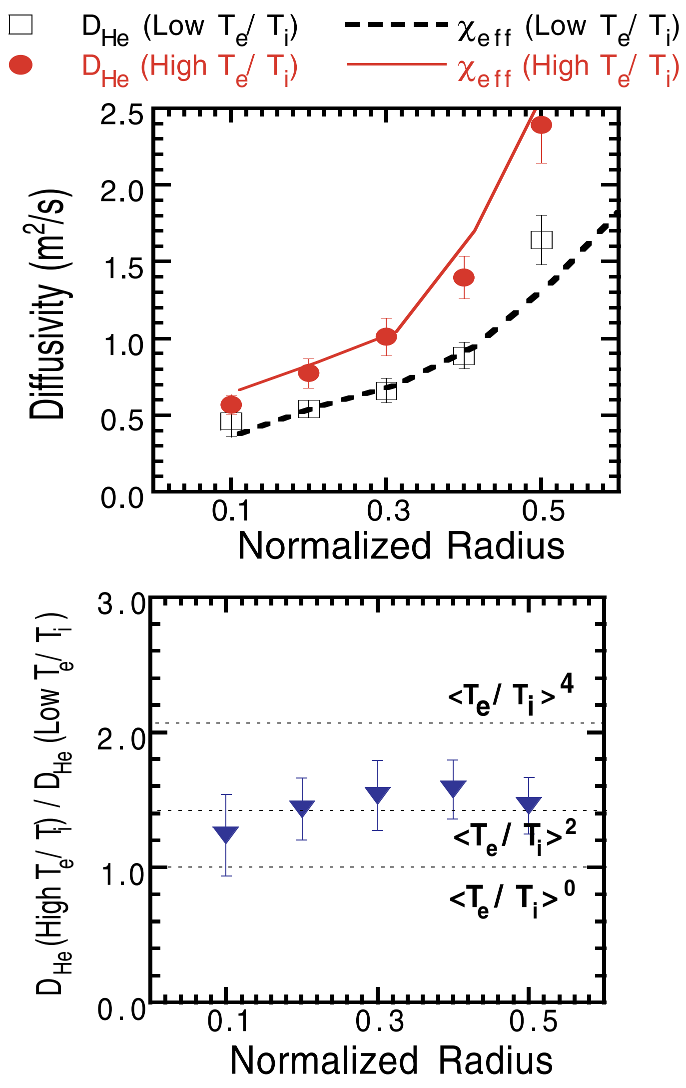
- Performed in ITER similarity discharges.



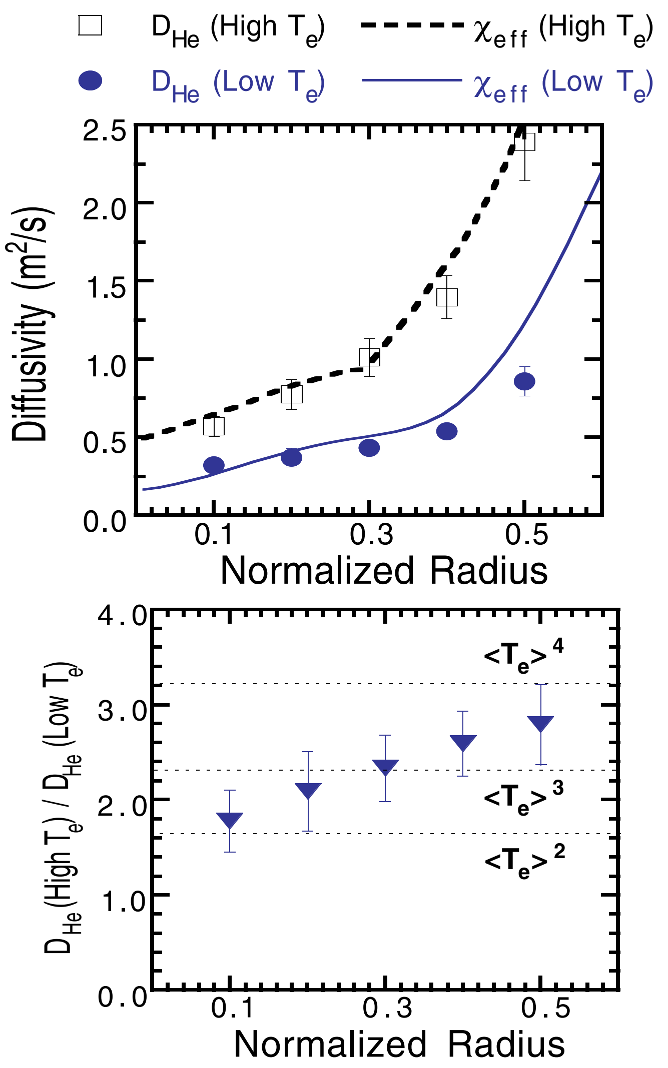
Normalized Radius Normalized Radius

Strong T_e/T_i Dependence is Observed for Both Helium Transport and Energy Transport in H-mode Plasmas

$T_e/\ T_i$ i Scan at Fixed Beta



T_e Scan at Fixed T_i



Transport Data Is Consistent with a Simple Linear Combination of Both Turbulence-Driven and Collision-Driven (i.e., Neoclassical) Transport

Model: Total radial particle flux can is a linear combination of the turbulence-driven and neoclassical particle fluxes.

$$\Gamma_Z = \Gamma_Z^{\text{turb}} + \Gamma_Z^{\text{neoc}}$$

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

$$D_Z^{\text{turb}} - \chi_{\text{eff}}; \quad V_Z^{\text{turb}} - D_Z^{\text{turb}} \nabla n_e / n_e$$

$D_Z^{\text{neoc}}, \quad V_Z^{\text{neoc}}$ calculated by NCLASS code

Physics Basis for Model:

- **Turbulence-driven transport is due to collective mechanisms associated with a fluctuating electric field with characteristic wavelengths in the mm to cm range.**
- **In contrast, collisional transport results from momentum exchange in binary collisions with characteristic collision scale lengths that are much smaller than the ion gyroradius.**

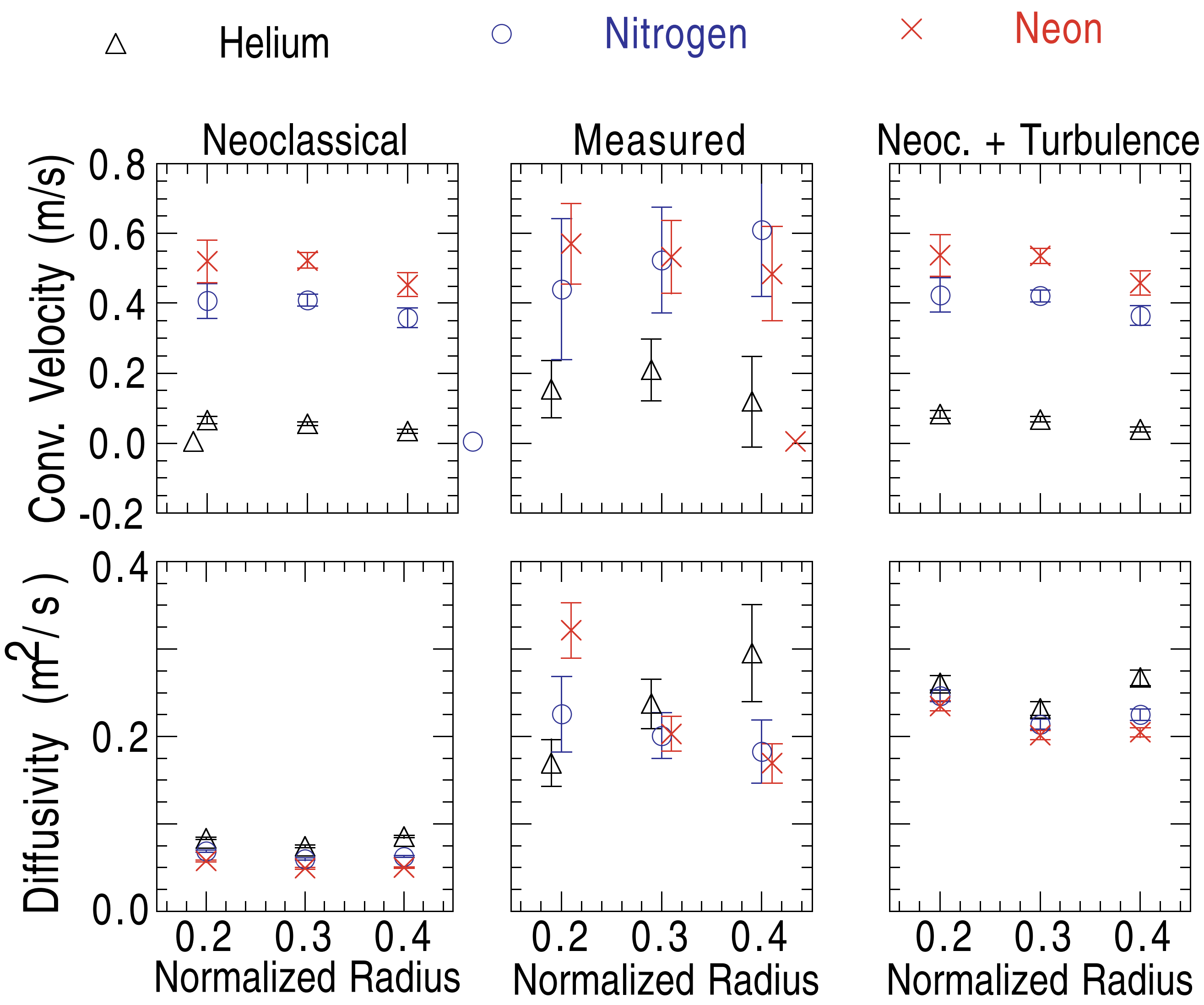
==> Hence, turbulence-driven and collision-driven transport should be decoupled.

- Electron particle and energy diffusivity is generally found to be much larger than the neoclassical predicted values. ==> Electron profiles determined by turbulence-driven transport.

- Ion-temperature gradient models, though imcomplete as far as particle transport is concerned, typically predict paricle and energy transport to be closely linked. ==> $D \sim \chi$

- Particle transport due to electrostatic turbulence will be the same regardless of charge or mass ==> V/D similar for all species.

Model Reproduces Measured Diffusivity and Convective Velocity in VH-mode Plasmas



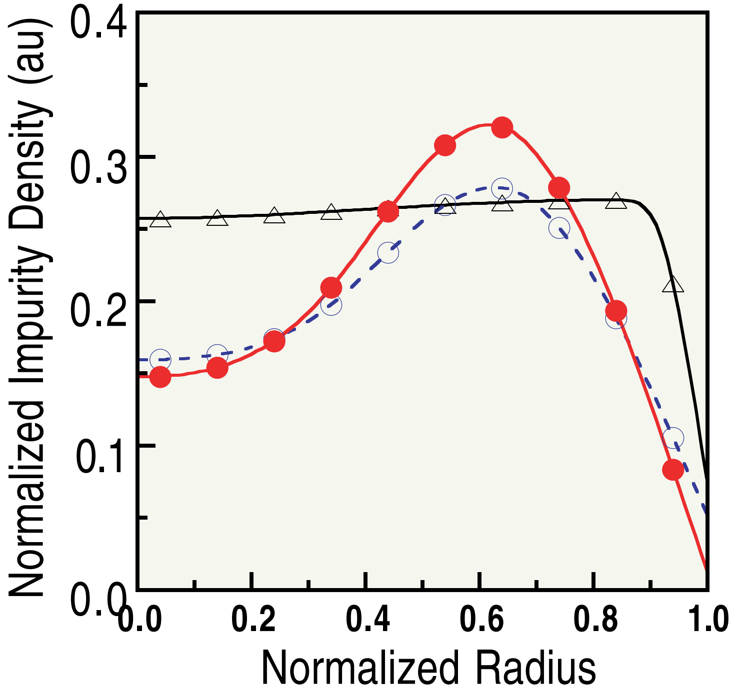
Model Reproduces Key Features of Measured Profiles in Both VH-mode and NCS Plasmas

Predicted Features:

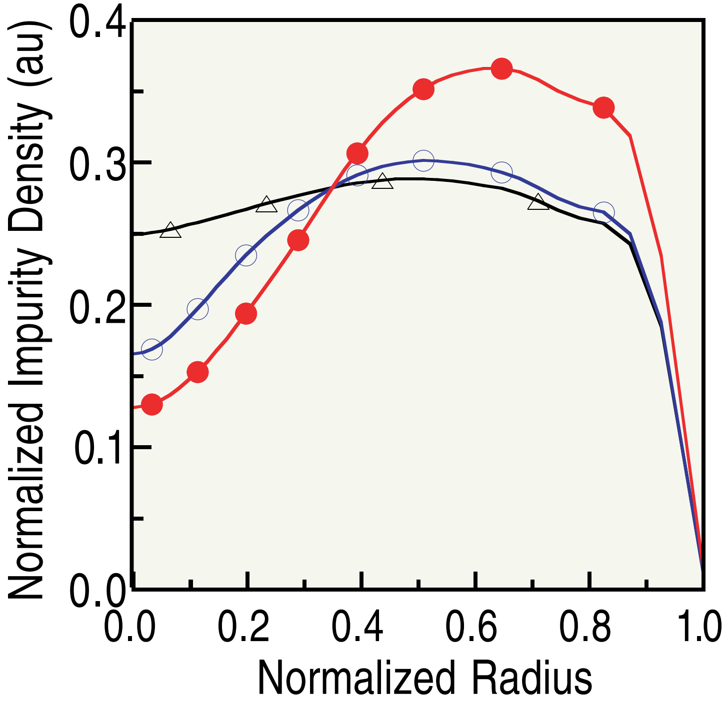
1) Helium density profile shape is nearly the same as the electron density profile
2) On-axis impurity accumulation on carbon and neon in NCS case
3) Hollow carbon and neon profiles in VH-mode case
4) Z dependence of the measured profiles is reproduced - note that profiles predicted by neoclassical transport alone do not match the measured profiles well.

VH-mode Comparison

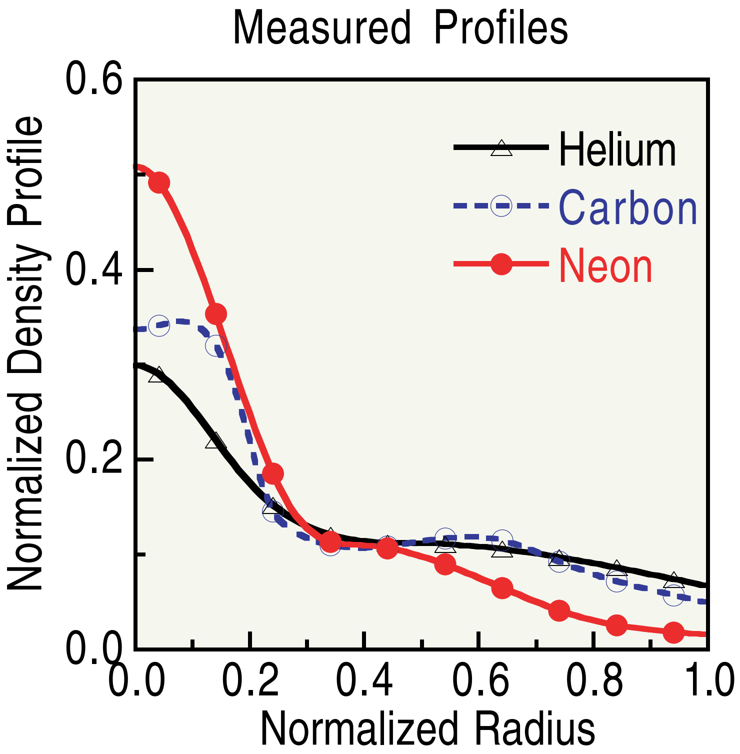
Measured Profiles

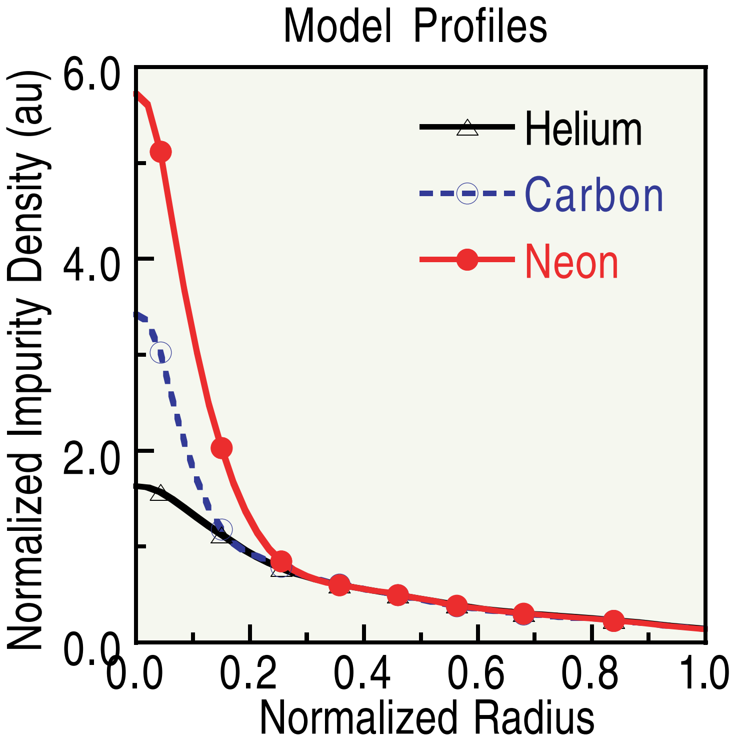


Model Profiles



NCS Comparison


Measured Profiles


Model Profiles

Implications of Model

- Due to the strength of the off-diagonal components of the neoclassical flux, this model has far reaching effects on the allowable impurity levels in fusion-grade plasmas.

- This is especially ture in situations in which energy confinement is improved through reduction in turbulence. While reduced turbulence is favoarable from an energy confinement standpoint, it can have deleterious effects on overall plasma performance due to unfavoarble particle transport characteristics inherent in neoclassical theory.

  - To test the impact of the model, we will apply it to future machines using the following model:

$$\Gamma_Z = \Gamma_Z^{\text{turb}} + \Gamma_Z^{\text{neoc}}$$

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

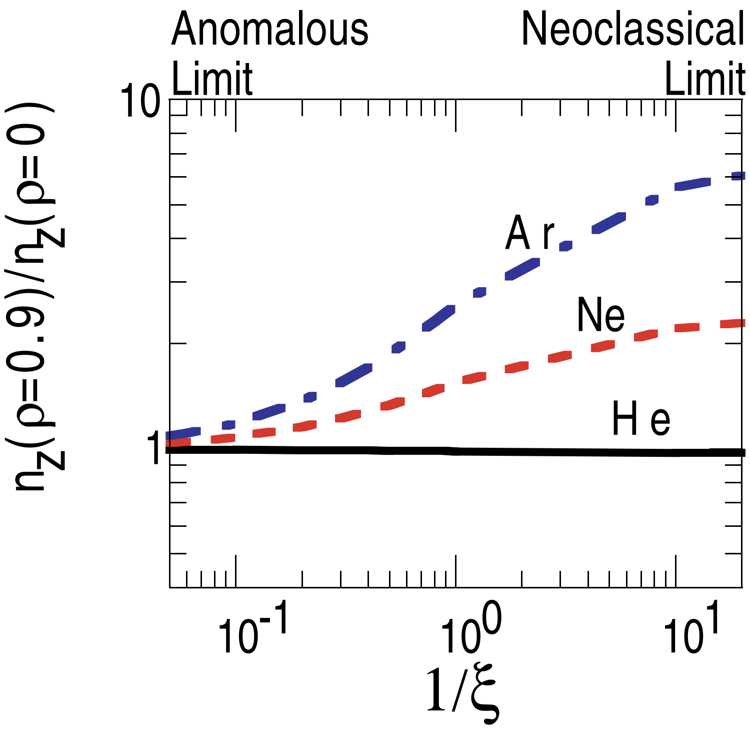
$$D_Z^{\text{turb}} \approx \xi D_D^{neoc}; \quad V_Z^{\text{turb}} \approx D_Z^{\text{turb}} \nabla n_e / n_e$$

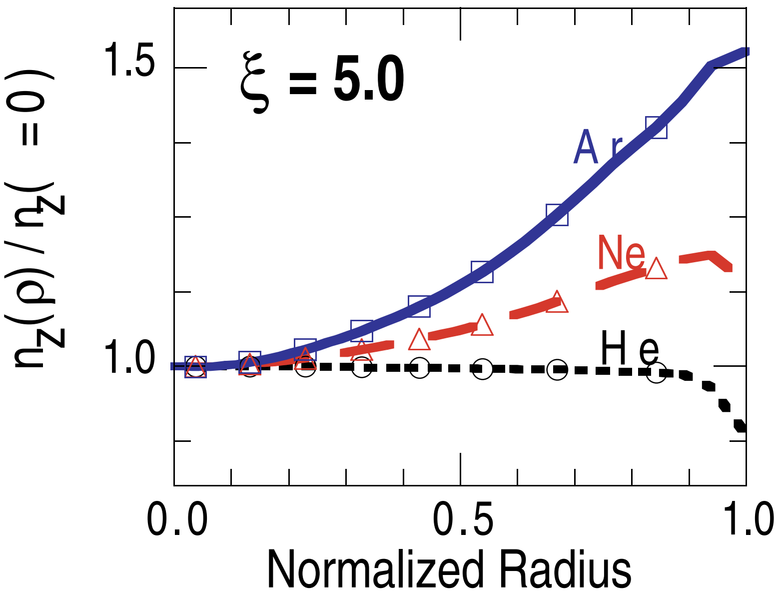
$D_Z^{\text{neoc}}, \quad V_Z^{\text{neoc}}$ calculated by NCLASS code

Model Predicts a Hollow Neon and Argon Density Profile in ITER even when Anomalous Transport is Much Larger than Neoclassical Transport

Solve $$n_Z(r) = n_Z(0)\exp\left\{\int\left(\frac{\xi}{1+\xi}\frac{V_{anom}}{D_{anom}} + \frac{1}{1+\xi}\frac{V_{neoc}}{D_{neoc}}\right)dr\right\}$$

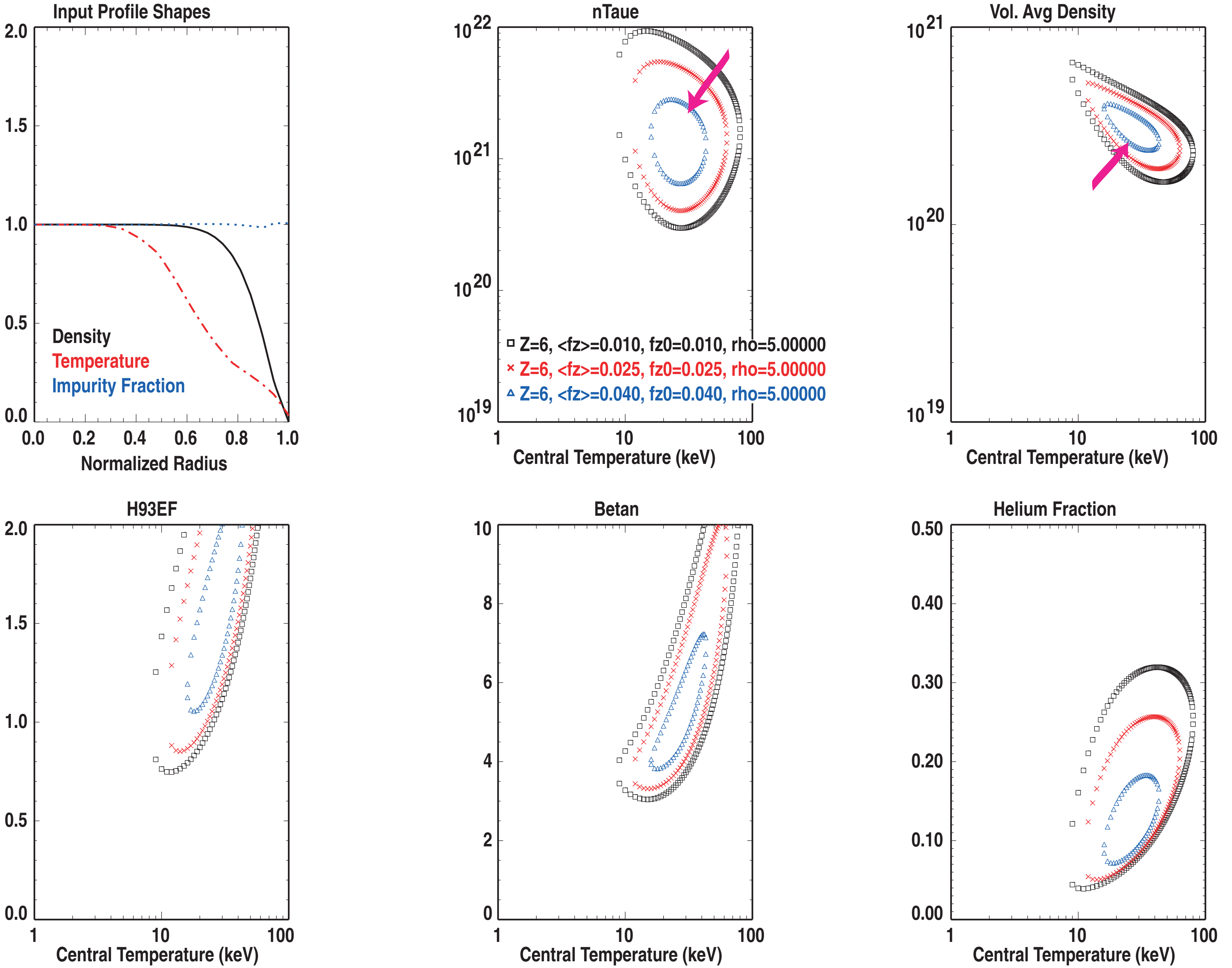
using ITER profiles and assuming $V_{anom}/D_{anom} = \nabla n_e/n_e$



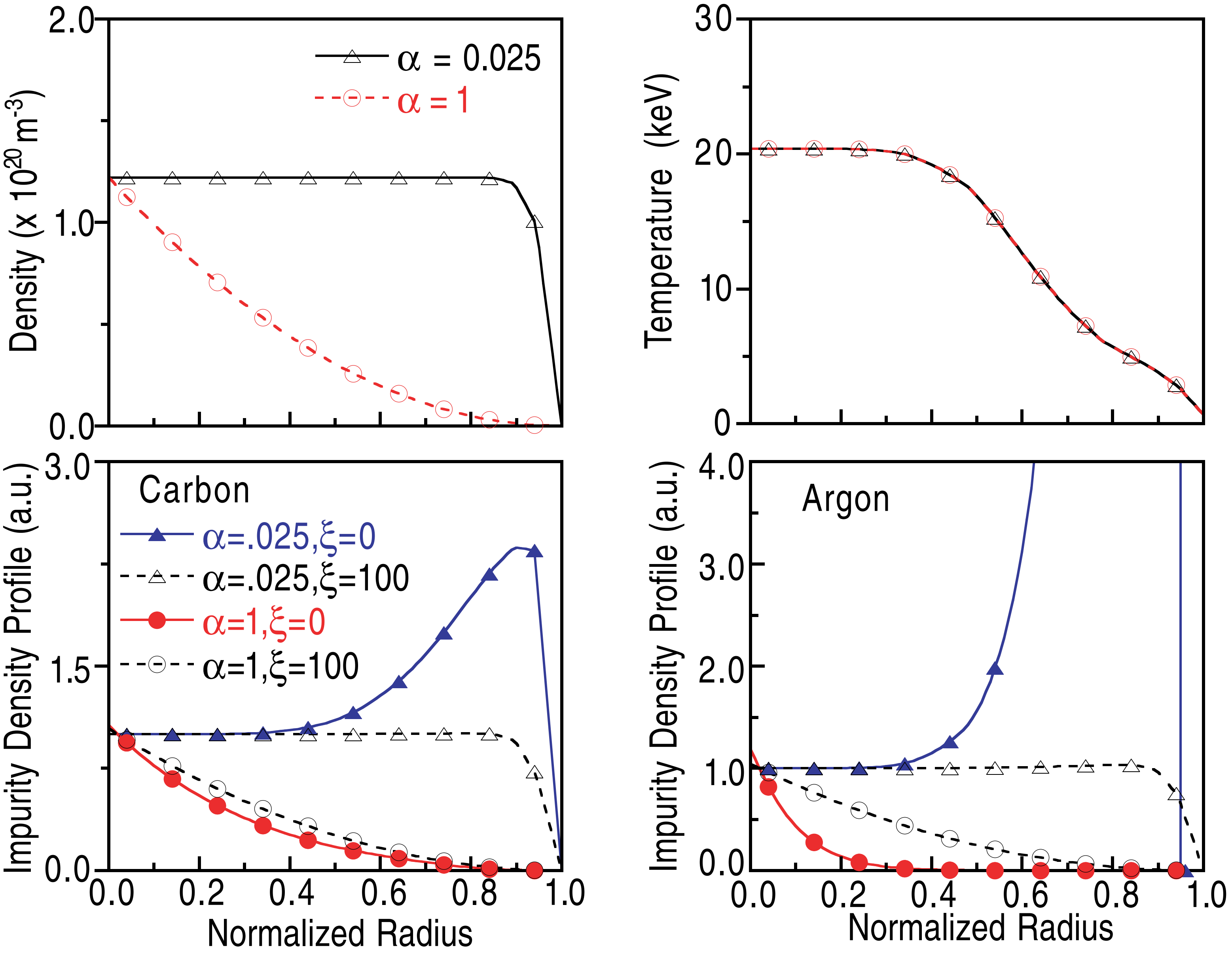


Basis of Ignition Contour Calculation (Following Reiter et al, NF 1990)

- Equations:
  - Power Balance $P_\alpha - P_{trans} - P_{brem} - P_{rad} = 0$
  - Helium Particle Balance $S_\alpha - S_{He,trans} + S_{He,recy} = 0$
- Produces a cubic equation for f_{He}. Solution is uniquely determined by specification of:
  - Relative helium confinement time $\rho = \tau^*_{He} / \tau_E$
  - Specifics of impurity contamination (I.e., Z of impurity and impurity fraction)
  - Temperature
- Assumptions
  - $T_e = T_i = T_Z$ $a(r) = a(0)a(r)$
  - Only one impurity other than helium
- Solution for f_{He} (and therefore $n\tau$) is independent of device parameters.

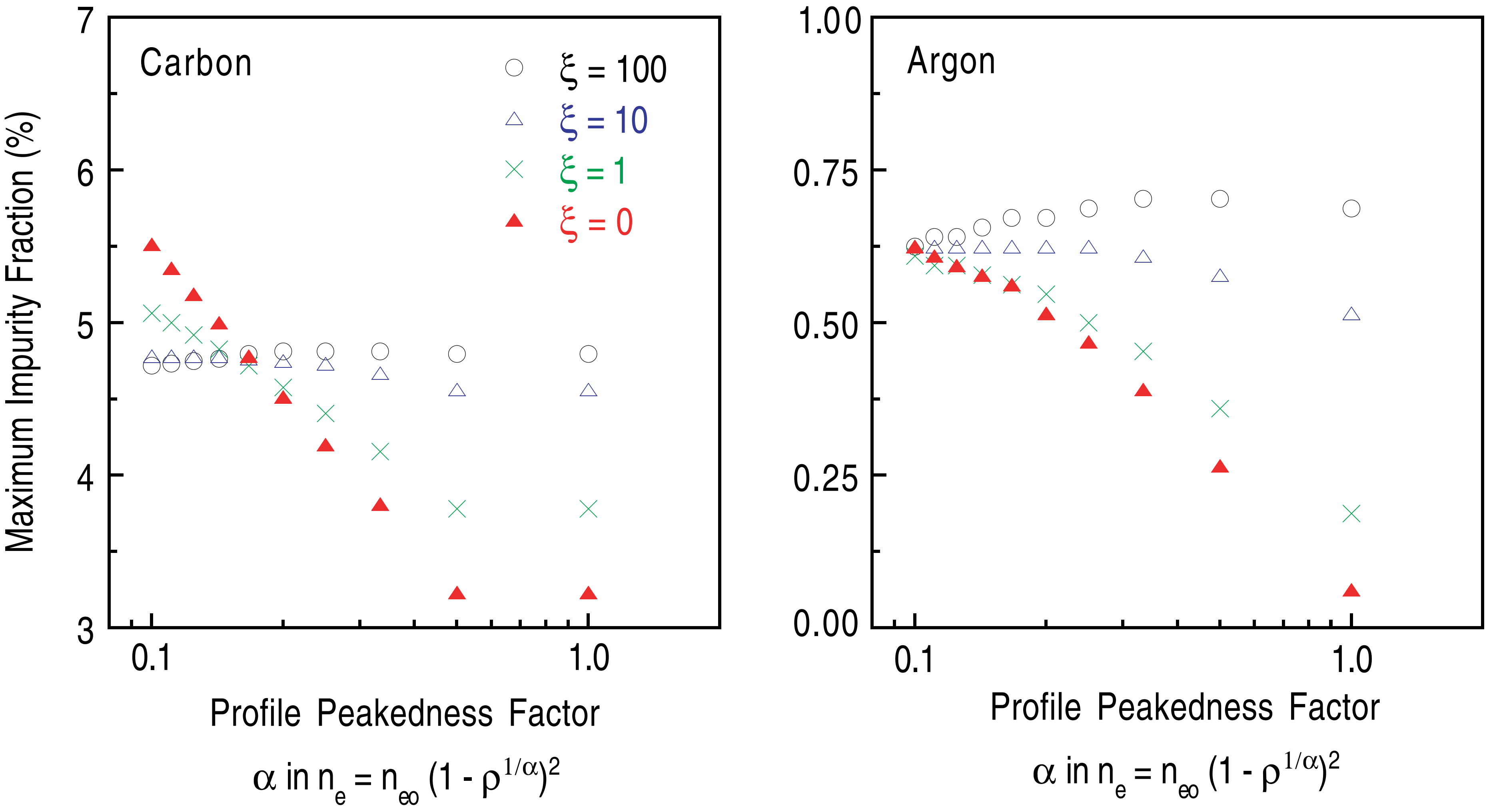

Input Profile Shapes
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Radius
Density
Temperature
Impurity Fraction
nTaue
10^{22}
10^{21}
10^{20}
10^{19}
1
10
100
Central Temperature (keV)
□ Z=6, <fz>=0.010, fz0=0.010, rho=5.00000
× Z=6, <fz>=0.025, fz0=0.025, rho=5.00000
△ Z=6, <fz>=0.040, fz0=0.040, rho=5.00000
Vol. Avg Density
10^{21}
10^{20}
10^{19}
1
10
100
Central Temperature (keV)
H93EF
2.0
1.5
1.0
0.5
0.0
1
10
100
Central Temperature (keV)
Betan
10
8
6
4
2
0
1
10
100
Central Temperature (keV)
Helium Fraction
0.50
0.40
0.30
0.20
0.10
0.00
1
10
100
Central Temperature (keV)

Impurity Density Profile is Strongly Dependent on the Assumed Density Profile and the Assumed Level of Turbulence

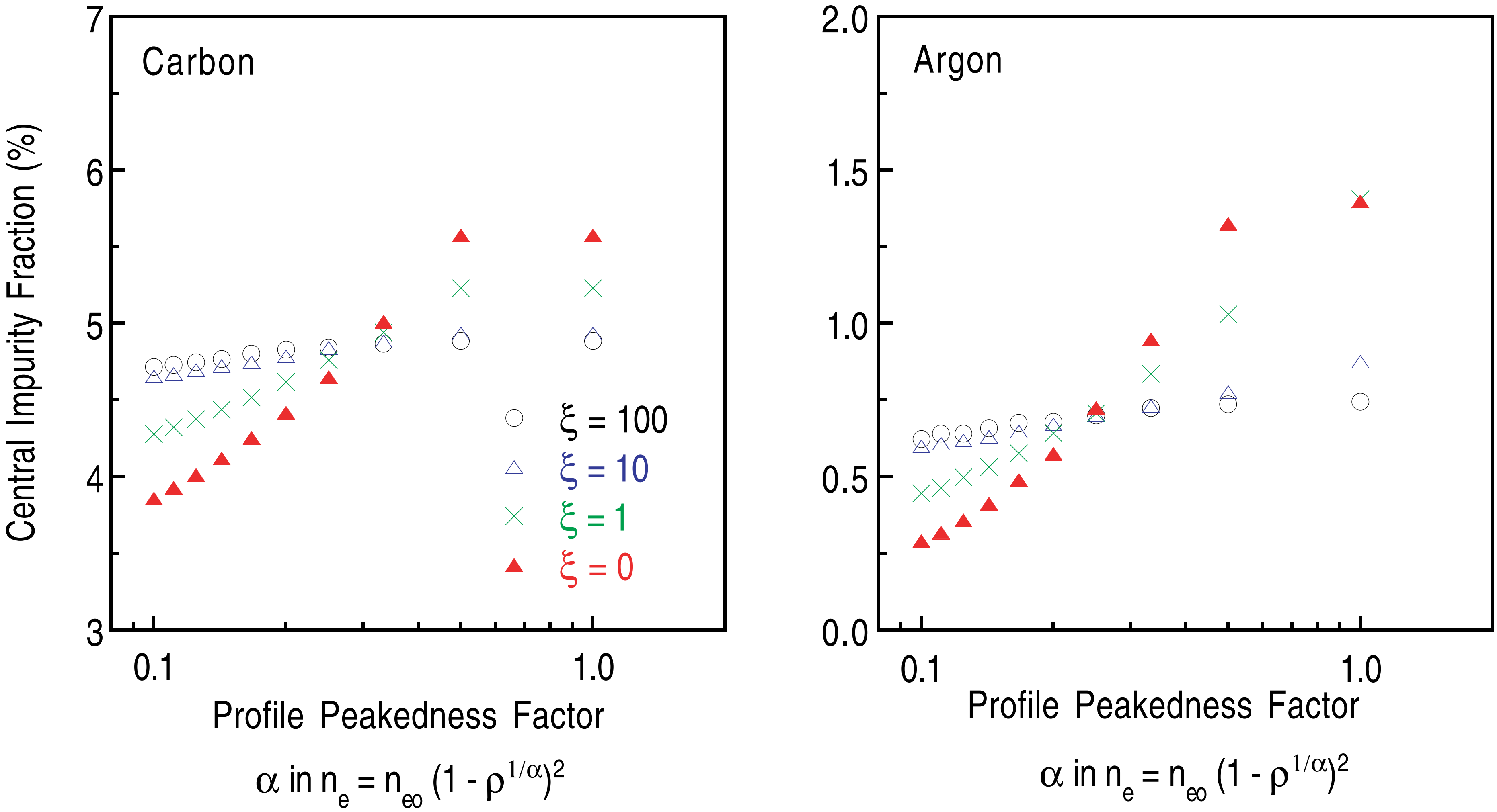


In Neoclassical Limit (ξ = 0), Maximum Allowable Impurity Fraction is Very Sensitive to Density Profile Peakedness, Especially for Argon

- Sensitivity Decreases as Level of Turbulence (i.e.,ξ) Increases



At Maximum Allowable Fraction Condition, Core Impurity Fraction is Much Lower in Flat Density Case ($\alpha = 0.025$) Than in Peaked Density Case ($\alpha = 1$)



Summary and Conclusions

Transport Model

- Simple linear sum of turbulence-driven and collision-driven (neoclassical) transport reproduces most of the experimental observations. In particular,
  - In highly turbulent plasmas (I.e., L-mode and H-mode), measured transport coefficients are well above the neoclassical values and $D_z \sim \chi_{eff}$.
  - In plasmas with reduced turbulence, evidence of the strong off-diagonal (I.e., convective component) of the neoclassical flux is evident.
    - Impurity peaking in NCS discharges
    - Impurity screening in VH-mode discharges.

Future Projections

- Profile effects are an important consideration in computing of the ignition window of a particular machine, especially in situations where ion neoclassical transport is expected.
- The ignition window is reduced considerably in the presence of peaked profiles with the maximum argon fraction reduced to 0.03 %.
- Conversely, flat density profiles allow higher impurity fractions with low core fuel dilution and high density near the edge for efficient radiation.