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, \( V n_j \), is usually inward and non negligible

- \( V \) can have Neoclassical and Anomalous Components
THE CONVECTIVE VELOCITY HAS TURBULENT AND NEOCLASSICAL COMPONENTS

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<th>Neoclassical</th>
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<td>Thermal Screening $\sim -0.5 \left( \frac{1}{T_i} \frac{\partial T_i}{\partial \rho} \right)$</td>
<td>$V_{Turb} \sim \frac{1}{T} \frac{\partial T}{\partial \rho}$</td>
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<td>Central Peaking $\sim z \left( \frac{1}{n} \frac{\partial n}{\partial \rho} \right)$</td>
<td>$V_{Turb} \sim -1 \left( \frac{1}{q} \frac{\partial q}{\partial \rho} \right)$</td>
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The Electron Particle Flux Equation

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

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

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 \( \Phi \) is the toroidal magnetic flux. \( \xi \) 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.
PLASMAS WITH HIGH TURBULENT TRANSPORT $n_e \propto (qH)^{-\xi}$

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

- Where $\Gamma_e \rightarrow 0$,

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

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.
IN H–MODE PLASMAS WITH NO INTERNAL TRANSPORT BARRIER, $n_e \propto (qH)^{-0.3}$
The neoclassical part of the impurity particle flux can be written as:

\[
\Gamma_{z}^{\text{neo}} = -D_{\text{neo}} \nabla n_{z} + n_{z} D_{\text{neo}} \left\{ \sum_{j} g_{j \rightarrow z} \frac{\nabla n_{j}}{n_{j}} + g_{T_{j}} \frac{\nabla T_{j}}{T_{j}} \right\}
\]

In steady state, with \( \Gamma \rightarrow 0 \), we obtain:

\[
\frac{n_{z}(\rho)}{n_{z}(0)} = \left[ \frac{n_{D}(\rho)}{n_{D}(0)} \right]^{g_{D \rightarrow z}} \left[ \frac{T_{i}(\rho)}{T_{i}(0)} \right]^{g_{T_{i}}}
\]

In the Banana Regime:

- \( g_{D \rightarrow z} \approx Z \) 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:
\[
\Gamma_z = \Gamma_z^{\text{turb}} + \Gamma_z^{\text{neoc}}
\]
\[
D_z = D_z^{\text{turb}} + D_z^{\text{neoc}}, \quad V_z = V_z^{\text{turb}} + V_z^{\text{neoc}}
\]

In most cases of interest, \( D_z^{\text{turb}} \gg D_z^{\text{neoc}} \)

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

\[
\frac{\nabla n_Z}{n_Z} = \frac{1}{1 + \xi_I} \frac{\nabla n_i}{n_i} + \frac{\xi_I}{1 + \xi_I} \left( Z \frac{\nabla n_i}{n_i} + g_T \frac{\nabla T_i}{T_i} \right)
\]

with \( \xi_I = D_{\text{neo}}/D_{\text{turb}} \)

- Result is less impurity accumulation than is predicted by neoclassical transport alone
DISCHARGES WITH ITB AND PEAKED DENSITY PROFILES SHOW CENTRAL IMPURITY ACCUMULATION

- Experimentally measured impurity accumulation is weaker than neoclassical and agrees with combined result.
In VH–mode plasmas with flat density profiles and peaked ion temperature profiles, the medium weight impurities accumulate near the edge.

![Graph showing impurity density and electron density profiles](image-url)
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,

\[ D_{\text{wow}} = \frac{\Gamma_e}{n_e} - \frac{1}{n_e} \frac{\partial n_e}{\partial \rho} - \xi \frac{1}{qH} \frac{\partial qH}{\partial \rho} \]  

(wow ~ WithOut Ware pinch)

Inclusion of the Ware pinch yields,

\[ D_e = \frac{\Gamma_e / n_e - V_{\text{ware}}}{1 - \frac{1}{n_e} \frac{\partial n_e}{\partial \rho} - \xi \frac{1}{qH} \frac{\partial qH}{\partial \rho}} \]

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 confinement, the two terms in the denominator no longer cancel and \( D_e \) is well defined.
REGION OF ENHANCED CONFINEMENT FOR $\rho < 0.5$ 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
The particle flux and the energy heat can have widely different dependence on plasma parameters.

\[
\chi_{\text{eff}} \equiv -\frac{q}{n} \frac{\partial T}{\partial \rho} \\
D_{\text{eff}} \equiv -\frac{\Gamma_e}{\partial n_e/\partial \rho} \\
q = q_i + q_e \\
T = T_i + T_e \\
n = \frac{n_i + n_i}{2}
\]
DIMENSIONLESS SCALING OF PARTICLE DIFFUSIVITY

- Direct Measurement of $D$ (and $V$) show that $D \sim \chi_{\text{eff}}$ or $\chi_i$
  - 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 $D_{\text{He}}$ scales as Bohm like. For H–mode plasmas $D_{\text{He}}$ scales like gyro-Bohm which is like $\chi_i$, $\chi_{\text{eff}}$ or $\chi_e$. $D_e$ scales between Bohm and Goldston. Both $D_{\text{He}}$ and $D_e$ scale close to $\chi_i$. 

![Graph showing dimensionless scaling of particle diffusivity]
DIMENSIONLESS SCALING AT PARTICLE DIFFUSIVITY

L–mode

H–mode

D_{He} (2T)/D_{He} (1T)

Normalized Radius

“Goldston”

Bohm

Gyro-Bohm

D_{He} (2T)/D_{He} (1T)

Normalized Radius

“Goldston”

Bohm

Gyro-Bohm

DIII-D

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SAN DIEGO

225-00/rs
GAS PUFF MEASUREMENTS SHOW THAT $D_{\text{He}}$ HAS SIMILAR MAGNITUDE AND RADIAL DEPENDENCE AS $\chi_{\text{eff}}$
GAS PUFF MEASUREMENTS SHOW THAT $D_e$ HAS SIMILAR MAGNITUDE AND RADIAL DEPENDENCE AS $\chi_{\text{eff}}$. 

**L–mode**

**H–mode**

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**DIII–D**

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STRONG $T_e/T_i$ DEPENDENCE IS OBSERVED FOR BOTH ENERGY AND HELIUM TRANSPORT IN H–MODE PLASMAS
In DIII–D NCS plasmas with ITBs, $D_e$ is more closely related to $\chi_i$ than $\chi_e$.

For many DIII–D plasmas with ITBs, $\chi_i \Rightarrow \chi_{\text{neoclassical}}$, while $\chi_e$ remains high. In these plasmas, $D_e \Rightarrow D_{\text{neoclassical}}$.

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 \( \chi_i \) \( \sim \) 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