



A Computational Study of Impurity Transport with PENTA

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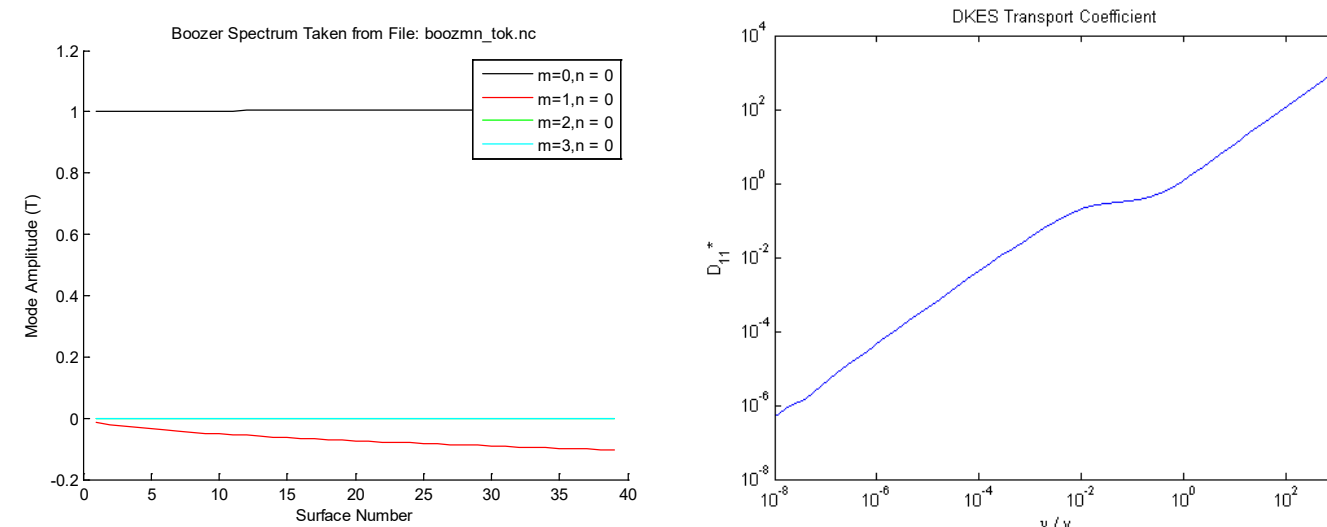
Overview

- Impurity accumulation is an important consideration in moving towards a stellarator / heliotron reactor.
- The PENTA code [1] has been extended to allow an arbitrary number of ion species, making it useful for use in impurity transport analysis.
- PENTA modifies the transport coefficients calculated by DKES to account inter-species coupling
- Benchmarking of PENTA for impurity analysis has been performed for a pure axisymmetric tokamak, reproducing the expected accumulation and expulsion behaviors.
- This analysis was then extended to predict convective velocities in the HSX stellarator, which show impurity expulsion near the core, and accumulation in the edge

Large Aspect Ratio Tokamak Test Case

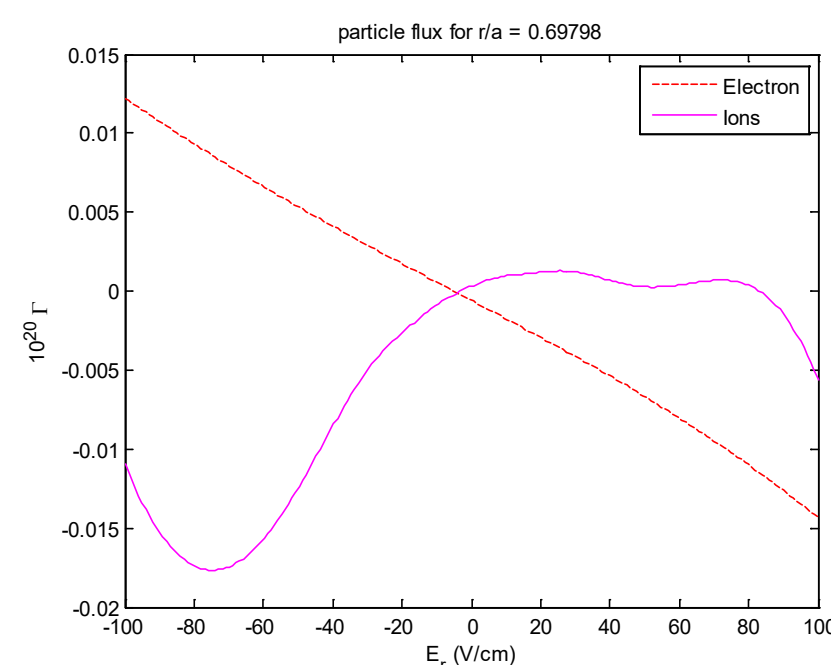
Benchmark Device

- Ideal Axisymmetric Equilibrium
- Circular Flux Surfaces in Vacuum
- $R = 1.211$ m
- $a = .126$ m
- $B_0 = 1$ T
- $I_{ota} = 1.04$
- $\beta \sim 0$

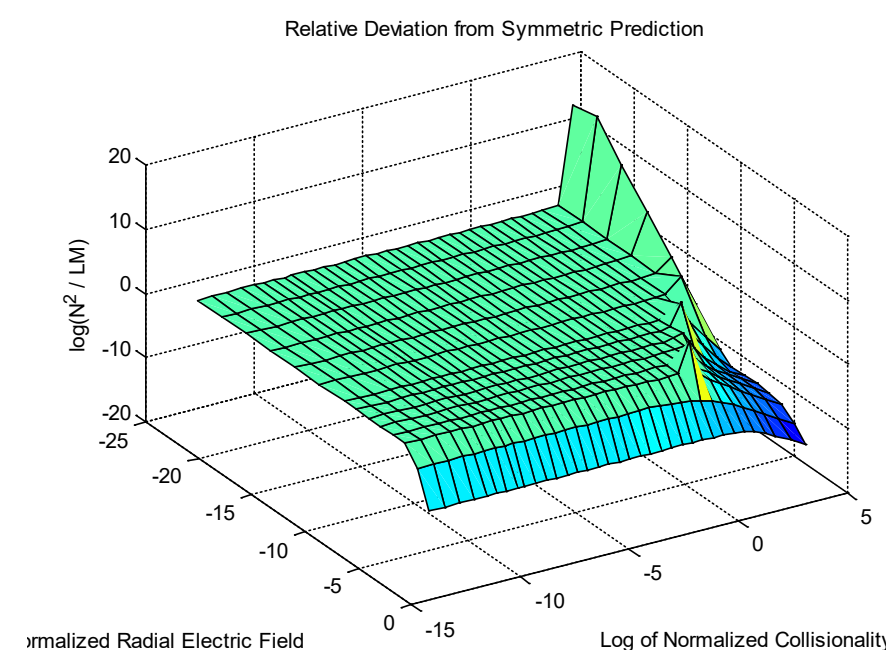


Intrinsic Tokamak Ambipolarity Not Reproduced

This issue may be due to a dependence of the DKES viscosity coefficients on the radial electric field [2]. For the rest of this work considering the axisymmetric case, $E_r = 0$ has been used to avoid this problem.



In a tokamak, the transport should be ambipolar, regardless of radial electric field. That result was not duplicable using DKES / PENTA. Ambipolarity is only seen near $E_r = 0$.



The L, M, and N monoenergetic transport coefficients should be related by the ratio: for all collisionalities and radial electric fields.

Large Aspect Ratio Tokamak Test Case (cont.)

Tokamak Impurity Transport Simulation

Simulation Parameters

- Plasma temperature:
 - $T_i = T_e = 50 - 7000$ eV
 - $\nabla T_i / T_i = \nabla T_e / T_e = 10$
- Plasma Density:
 - $n_e = 5 \times 10^{19} \text{ 1/m}^3$
 - $n_i = 0.01 \times n_e$
- Impurity Species: Carbon V
- Electric Field : $E_{||} = E_r = 0$

$$\Gamma_I = -D \nabla n_I + V n_I$$

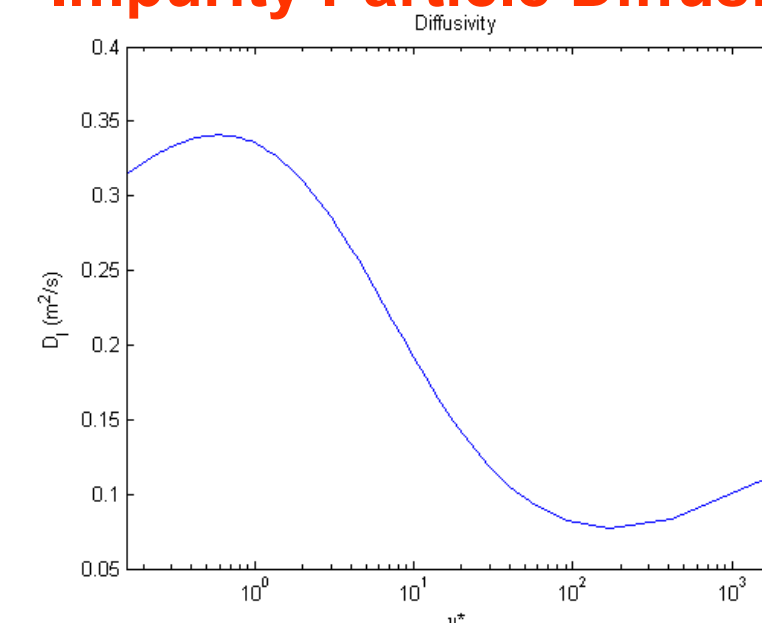
Diffusivity

Convective Velocity

$$\propto \nabla n_i$$

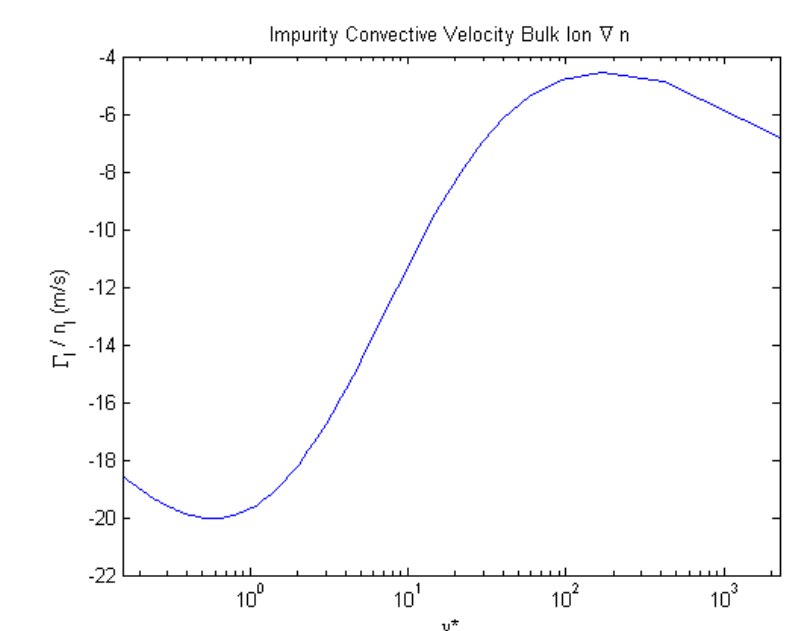
$$\propto \nabla T_i, \nabla T_e$$

Impurity Particle Diffusivity



- Peaking of the impurity density profile must balance any unfavorable convective transport

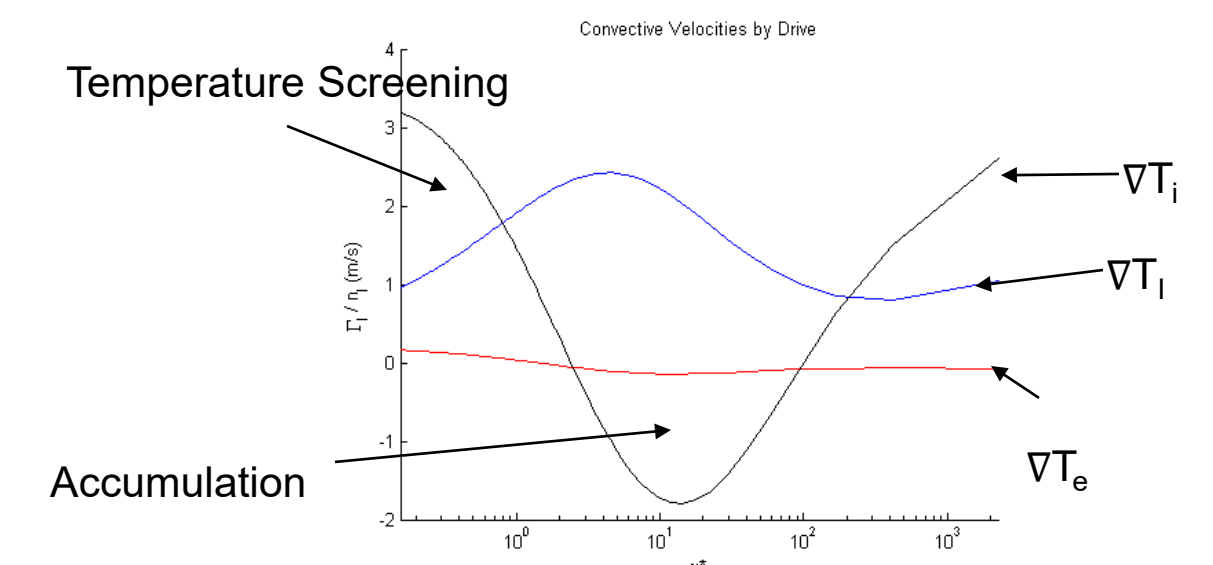
Accumulation Due To ∇n_i



- Friction on the bulk ions always drives accumulation

Temperature Gradient Driven Transport

- Sign of the transport from bulk species depends on collisionality
 - In banana regime, those temperature gradients cause impurity expulsion.
 - In Plateau, and near Pfirsch-Schluter regimes, they cause accumulation





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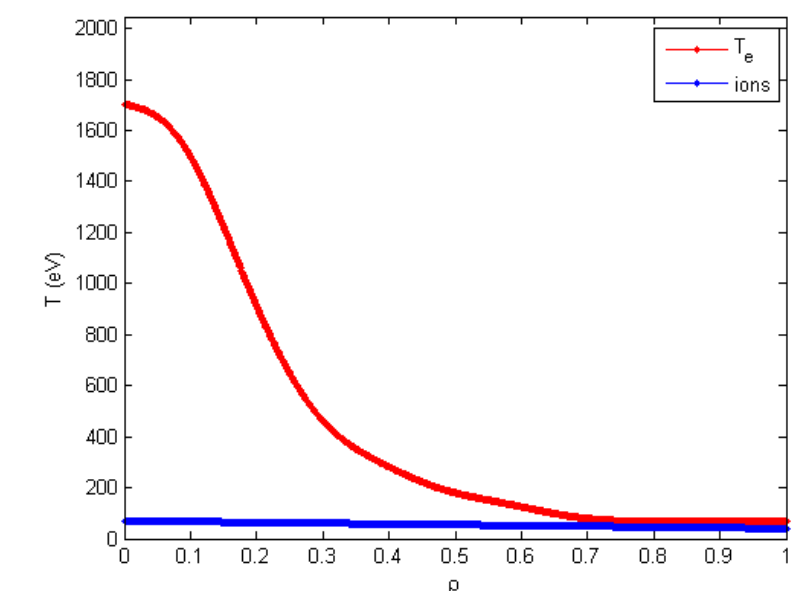
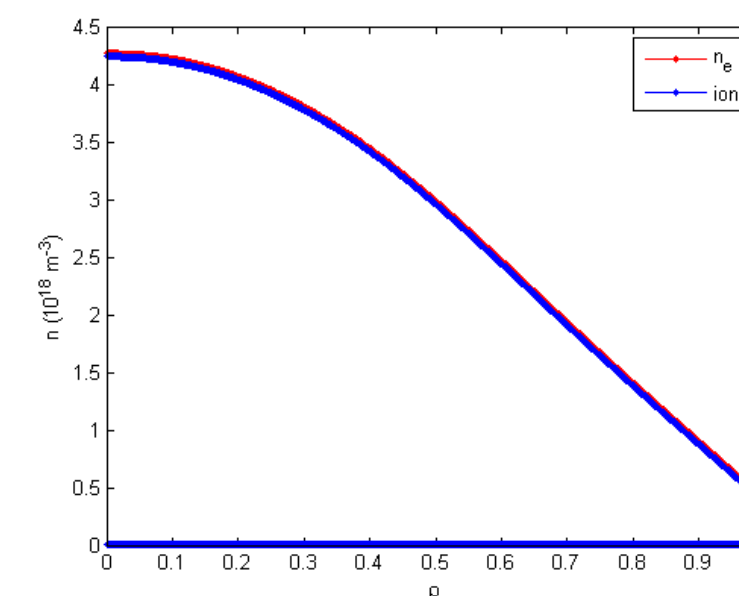
HSX Calculations

Overview

- In a stellarator, the equilibrium radial electric field is also a function of the temperature gradients, so temperature screening / accumulation becomes a non-linear problem.
- Plasma temperature and density profile are measured by Thomson scattering
- The Carbon V impurity is given a uniform trace density across the entire plasma
 - This non-physical situation only allows the prediction of the convective portion of the transport
- The radial electric field is calculated from the ambipolarity constraint.
 - Where two stable solutions exist, both are plotted.

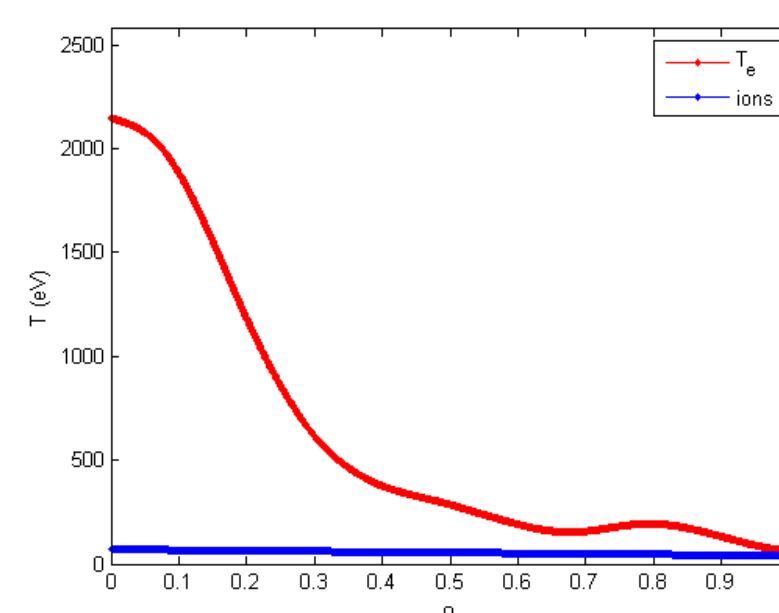
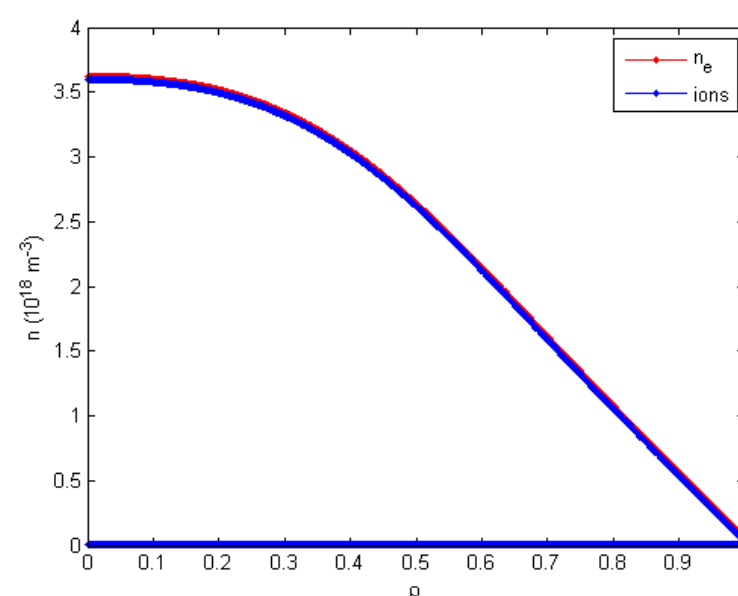
44 kW QHS

Plasma Profiles

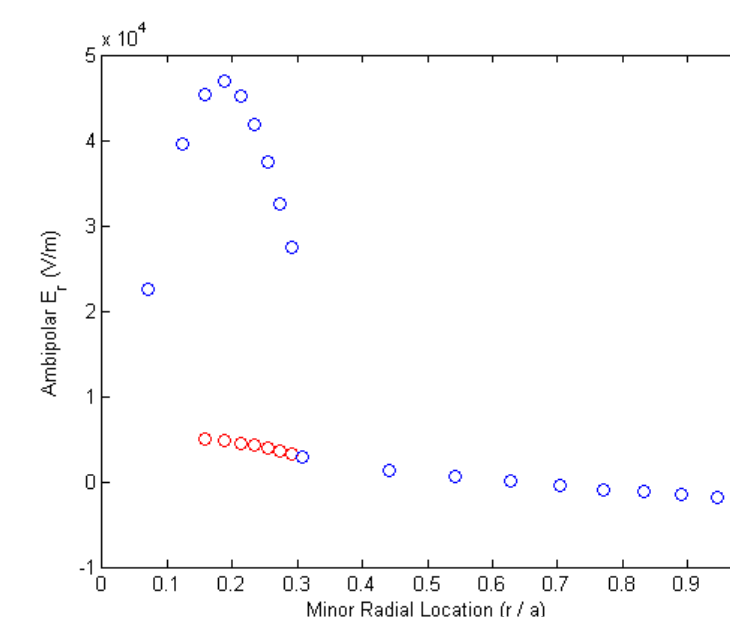


100 kW QHS

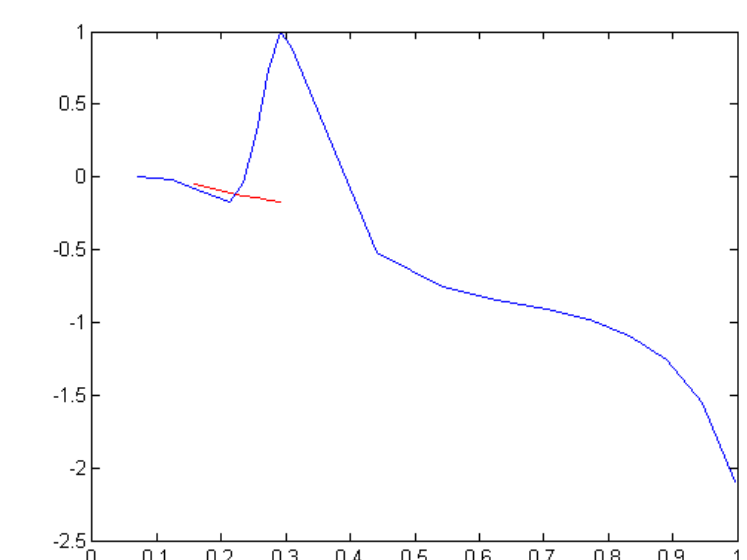
Plasma Profiles



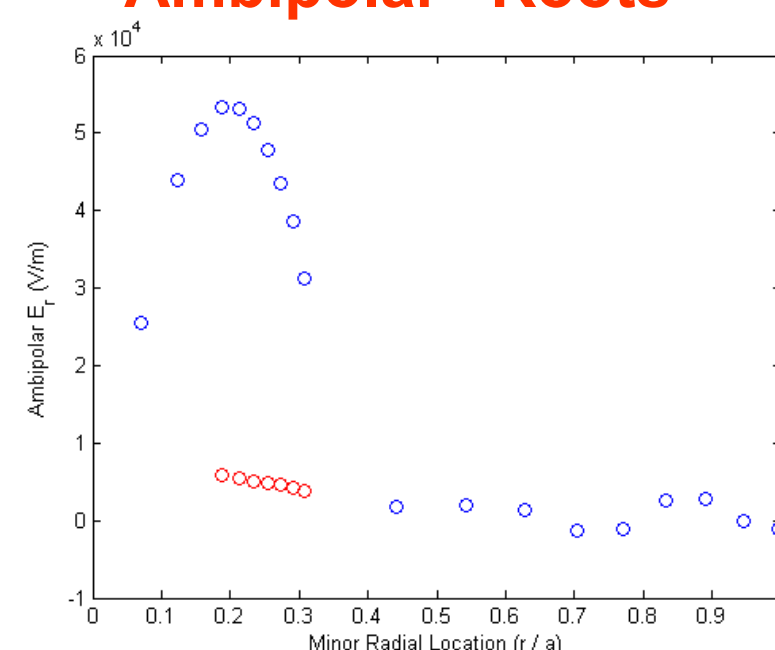
Ambipolar "Roots"



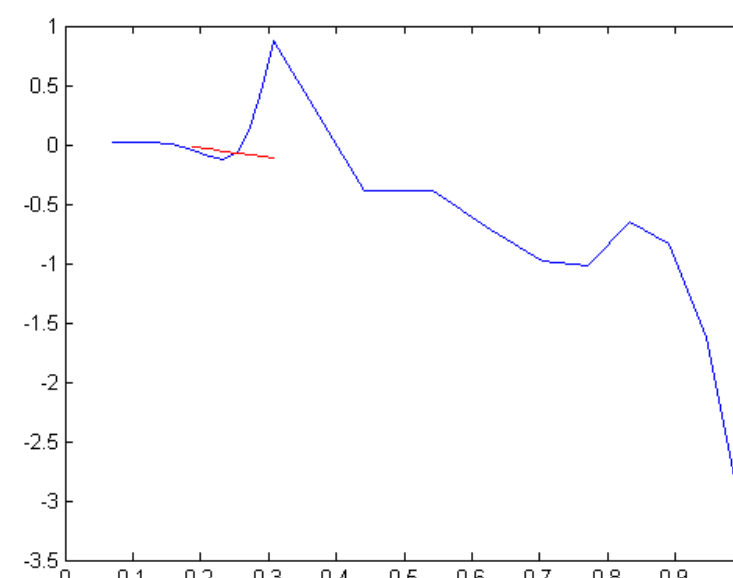
Impurity Convective Velocities



Ambipolar "Roots"



Impurity Convective Velocities



References

- 1) H. Sugama and S. Nishimura, "How to calculate the neoclassical viscosity, diffusion, and current coefficients in general toroidal plasmas," *Physics of Plasmas* 9 (2002): 4637.
- 2) S. Nishimura, Private Correspondence, September 2009.

Summary

- Ambipolar tokamak transport is not reproduced by DKES / PENTA
- Tokamak calculations meet expectations for impurity transport
- In HSX PENTA predicts impurity expulsion in the core, due to favorable radial electric field and temperature gradients.