Issues and recent developments in edge plasma modeling encompassing the pedestal and SOL regions*

T.D. Rognlien

Fusion Energy Program

LLNL

(In collaboration with R. Cohen, B. Cohen, L. LoDestro, B. Nevins, M. Umansky, X. Xu; J. Brooks, A. Kubota)

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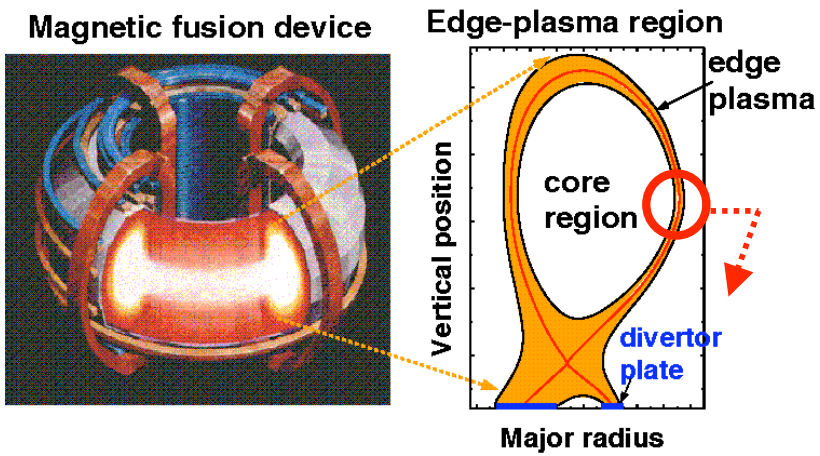
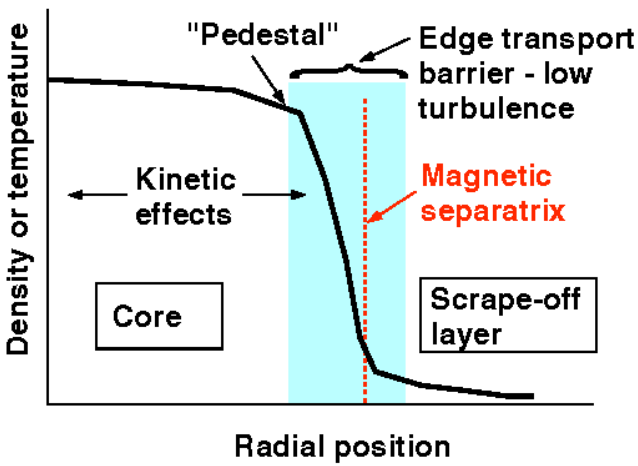
Edge plasma understanding & control is crucial to the success of Magnetic Fusion Energy devices



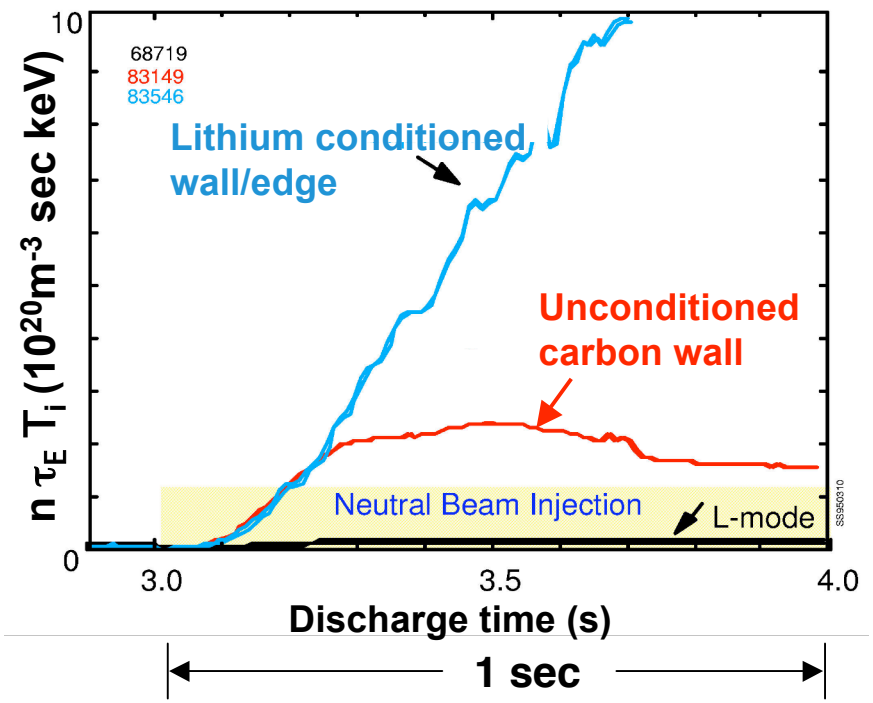


$$\Gamma_n = -D dn/dr + V_{conv} n$$

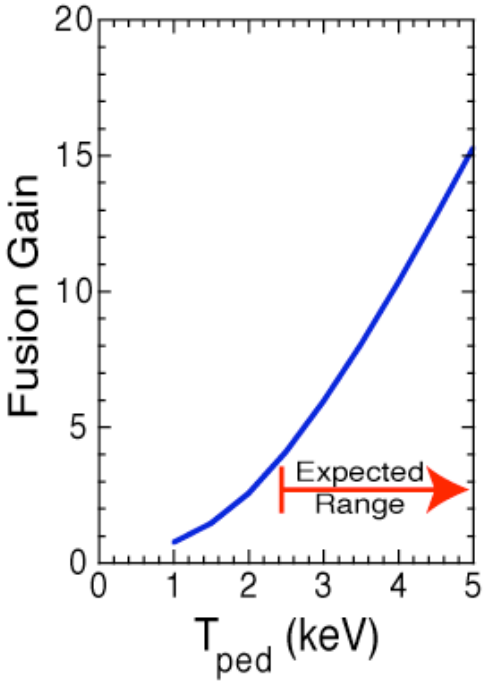
- **Edge plasmas mediate between hot core and material surfaces**
  - Plasma power exhaust
  - Helium ash removal
  - Wall impurities and recycling
- **Edge plasmas also have a major effect in core performance**
  - Edge transport barriers
  - Periodic profile relaxation: Edge-Localized-Modes (ELMs)

Experiments and theory show edge-plasma conditions have a major impact on core energy confinement

Confinement time in TFTR tokamak



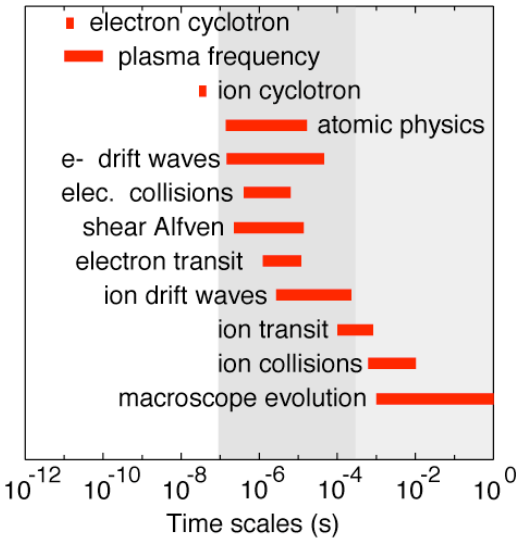
Fusion gain in ITER projected from assumed edge temp.

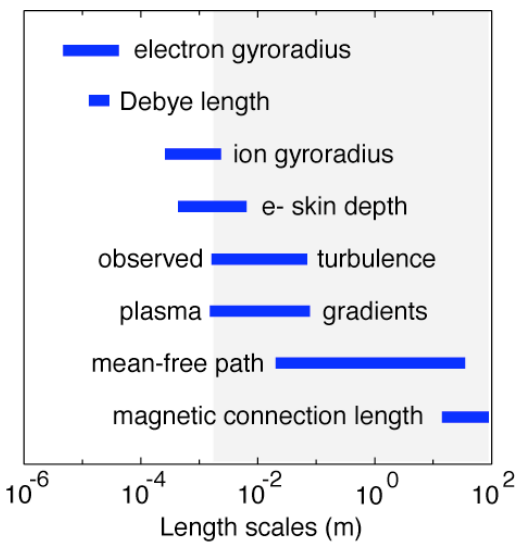


Quantitative prediction of T_{ped} requires self-consistent coupling of edge turbulence and transport

Edge region has very wide ranges of time and space scales, and its behavior has a large impact

Scales to be resolved





Key physics/eng. issues

- **H-mode transport barrier**
- **ELM stability/transport**
- **Density limit**
- **Wall erosion; impurity production**
- **Tritium recovery**
- **…**

The pedestal, scrape-off layer, and walls are strongly interdependent

- **Radial gradients comparable to**
  - turbulence correlation lengths
  - ion poloidal gyroradius

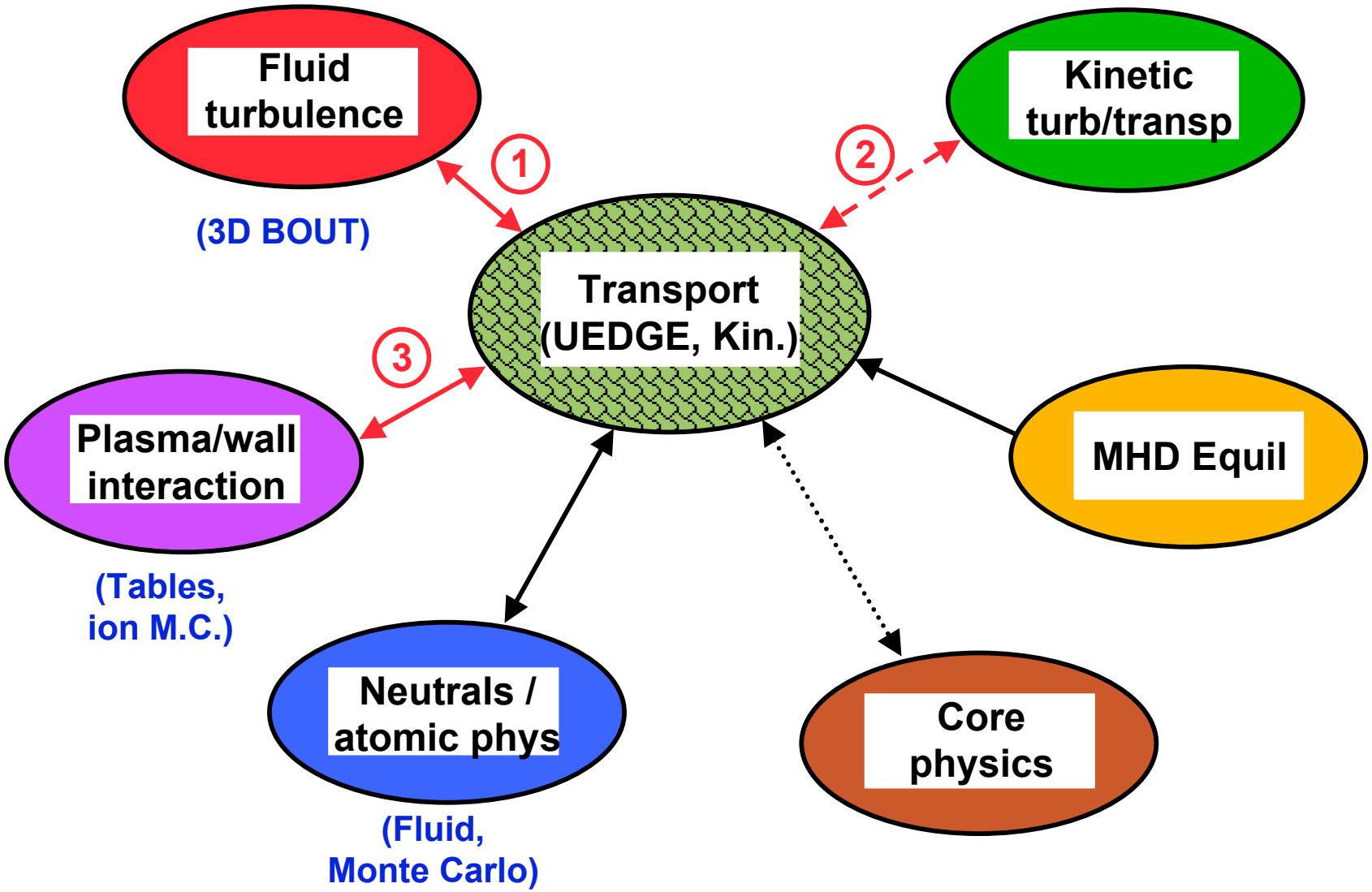
- **Collisionality regime rapidly changes**
  - often in banana regime at top of pedestal [$\nu/(v_t L_{||}) << 1$]
  - Pfirsh-Schlüter regime in the SOL [$\nu/(v_t L_{||}) >> 1$]

- **Strong magnetic shear at separatrix strongly impacts turbulence**

- **Neutral wall fluxes can provide sources through whole region**

Strong coupling of regions makes integration essential

An integrated Edge Module requires many components (red arrows discussed today)



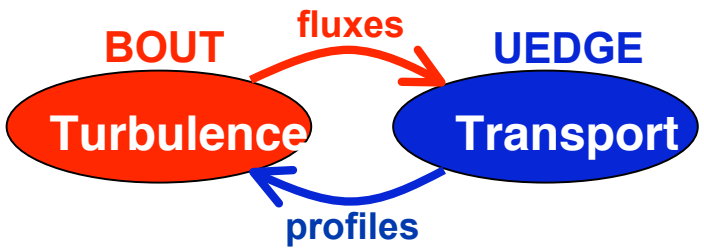
UEDGE and BOUT are oft-used fluid codes for 2D edge transport and 3D edge turbulence

- UEDGE solves for 2D edge plasmas profiles assuming toroidal symmetry
- Braginskii-type magnetized fluid equations
- Classical parallel transport with flux limits
- Classical ExB and grad_B drifts
- Ad hoc cross-field transport
- Fluid neutral model (with flux limits); some coupling to Monte Carlo neutrals

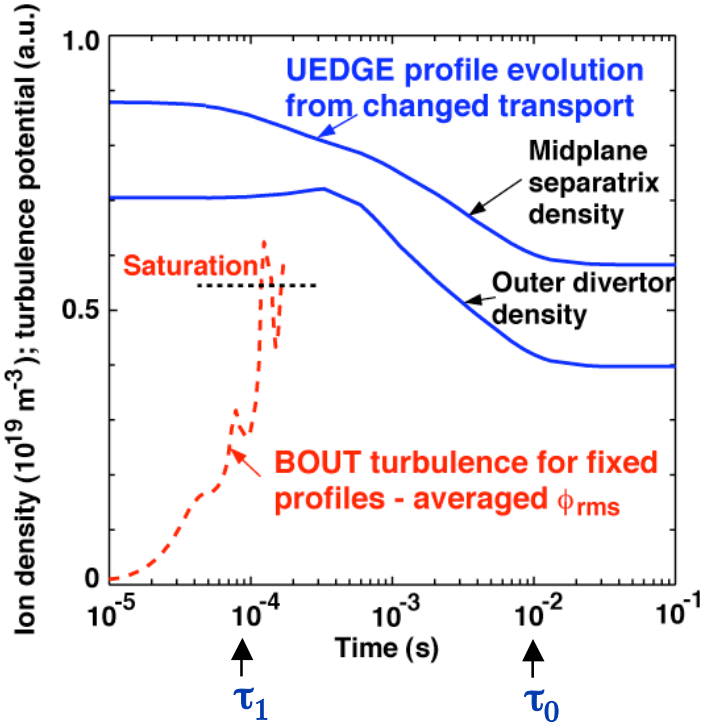
- BOUT solves for 3D, low-frequency, edge turbulence
- Braginskii-type magnetized fluid equations for n_i, $v_{||i}$, $J_{||}$, T_e, T_i, ϕ, and $A_{||}$
- Classical parallel physics and cross-field drifts
- Ad hoc plasma and neutral profiles (profile evolution beginning)
- BOUT and UEDGE share poloidal mesh from an MHD equilibrium

T&T coup

Coupling is effective because of widely different time scales for turbulence and transport



Comparison of transport and turbulence timescales

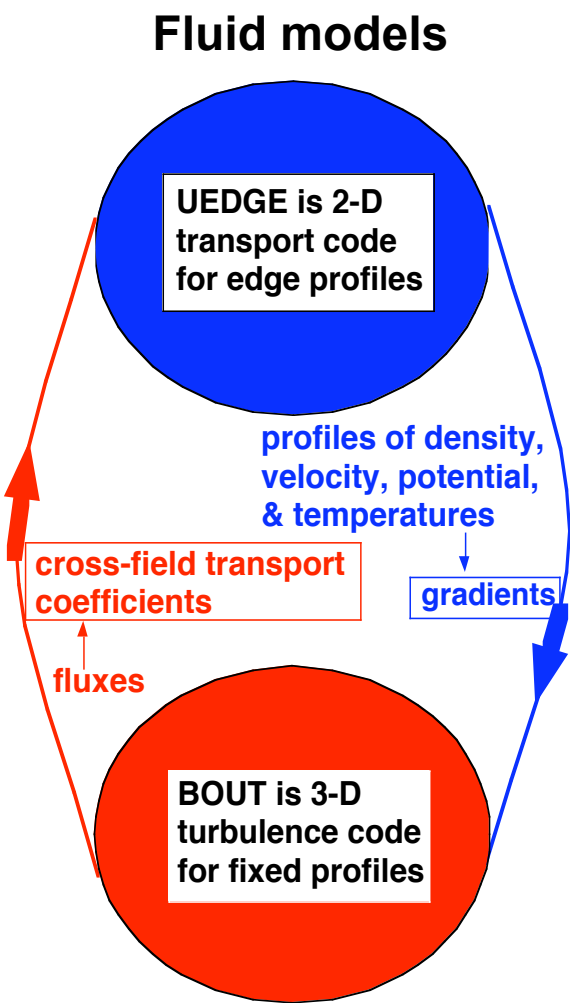


- BOUT turbulence is evolved for τ_1 ~ 0.05 - 0.1 ms
- UEDGE takes a larger time step, with τ_0 > 10 ms

- Initial coupling model yields steady-state
- Work progressing on time-dependent coupling

T&T coup

Transport & turbulence need to be evolved together; a major scientific challenge



- **We have made good progress**
  - coupled plasma variables (4)
  - included neutrals in transport
  - 2D domain decomp.; PYTHON interface
- **Presently extending in key areas**
  - Include radial E-field that forms transport barrier
  - Extend coupling to time-dependence; expt. comparisons
  - Add kinetic corrections to improve high T_{ped} regime (e.g., ITER)

T&T coup

UEDGE evolves plasma & neutral continuity, momentum, & energy equations

Continuity and momentum equations are solved for plasma & neutrals

$$\partial N_k / \partial t + \mathrm{div}(N_k V_k) = S_{pk}$$

$$\partial (N_k m_k V_{||k}) / \partial t + \mathrm{div}(N_k m_k V_{||k} V_k) = -\mathrm{grad}_{||} P_k + q N_k E_{||} - F_{||k} - R_{||k}$$

where k = i/g for ions/neutrals; T_e and T_i eqns. now included

Perpendicular neutral velocity is CX dominated:

$$V_{\perp g} = V_{\perp i} - [1/(m_g N_g n_g)] \, \mathrm{grad}_{\perp} (N_g T_g)$$

The ion cross-field transport comes from BOUT's radial flux Γ_r giving

$$D_i = \max [-\alpha_2 \Gamma_r / (dN_i/dr), 0.01] \quad (m^2/s)$$

$$V_{conv} = (1 - \alpha_2) \Gamma_r / N_i \quad (m/s)$$

T&T coup

Coupling algorithm uses an iteration over index m; UEDGE & BOUT evolved on own time scales

Continuity equation is solved for 2D, axisymmetric plasma & neutrals

$$\partial N_i^m / \partial t + \mathrm{div}(N_i^m V_{||i}^m + \Gamma_r^{m-1}) = S_{pi}^m$$

Perpendicular turbulent particle flux comes from BOUT:

$$\Gamma_r^{m-1} = (1 - \alpha_1)\, \Gamma_r^{m-2} + \alpha_1 < n_i v_{ri} >^{m-1}$$

where α_1 is a relaxation parameter (~0.25). Likewise, the ion profile in BOUT is updated according to

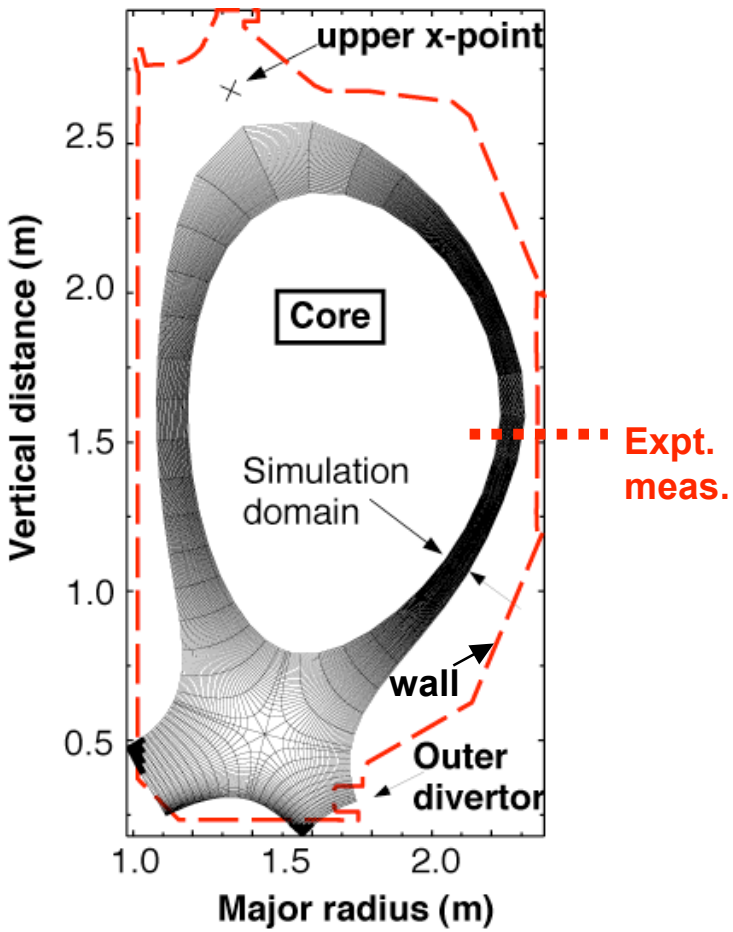
$$N_i^{m-1} = (1 - \alpha_0)\, N_i^{m-2} + \alpha_0\, N_i^{m-1}$$

where α_0 is a second relaxation parameter (~0.5). The parallel ion velocity, $V_{||i}$, is similarly updated from UEDGE to BOUT.

T&T coup

UEDGE and BOUT coupling uses actual experimental toroidal geometry and data

MHD equilibrium mesh used for DIII-D simulation



- Plasma parameters provided by DIII-D personnel
- We have coupled cases for both fixed and evolving temperature profiles
- Fluxes represented in the form

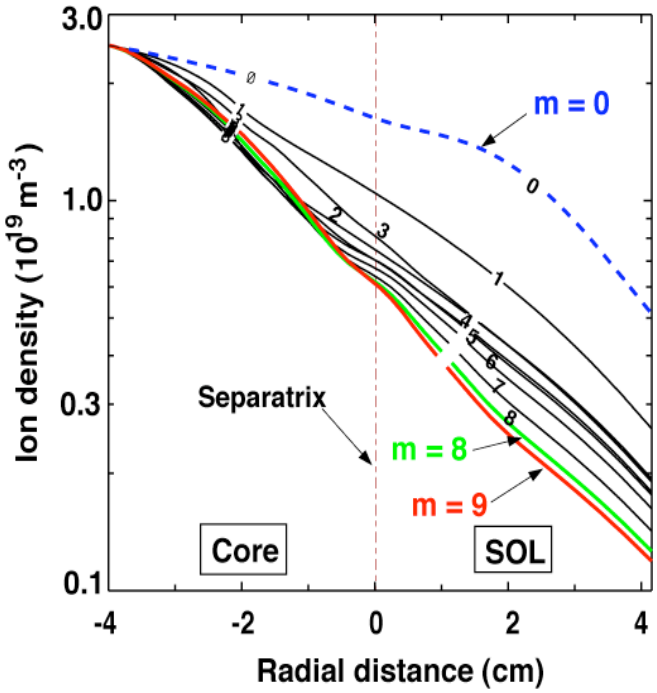
$$\Gamma_n = \langle n_1 v_1 \rangle = -D dn/dr + V_{conv} n$$

T&T coup

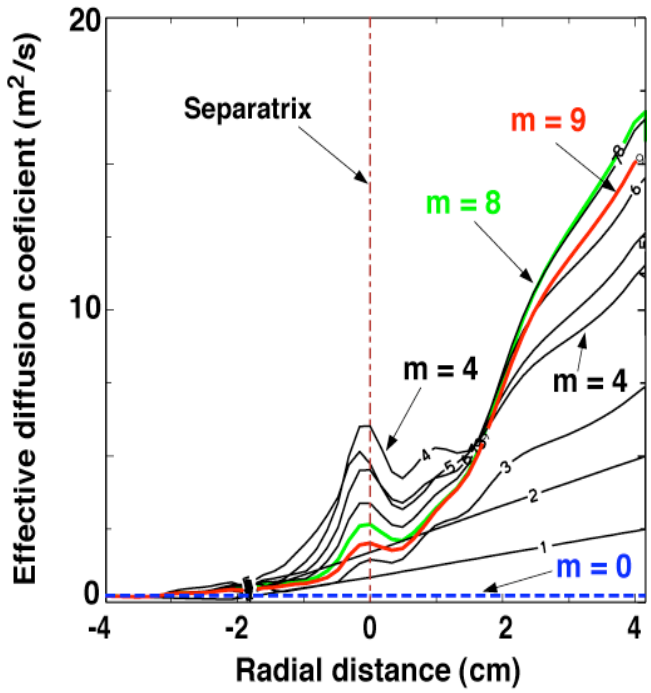
We have achieved self-consistent edge turbulence/transport simulations

Coupling iteration index is m

a) Midplane density profile evolution



b) Midplane diffusion coeff. evolution

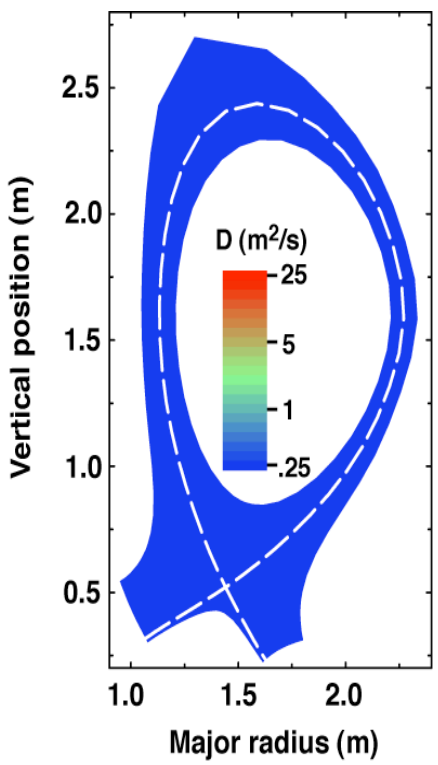


- **Density profile converges more rapidly than turbulent fluxes**

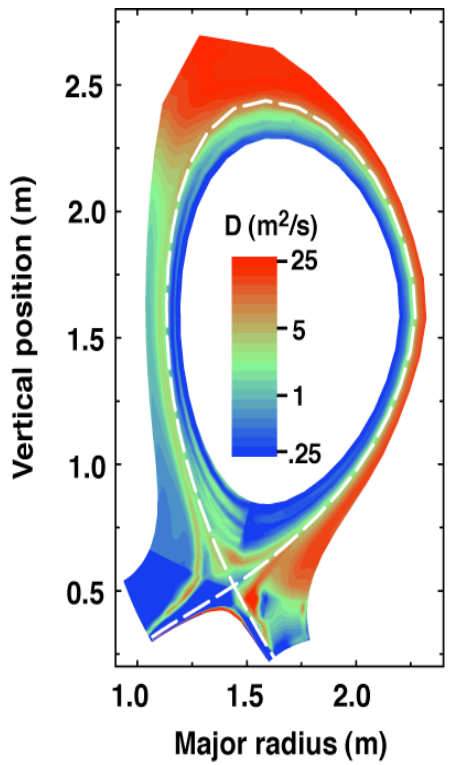
T&T coup

Results show that strong spatial dependence of transport must be included

a) Typical previous model



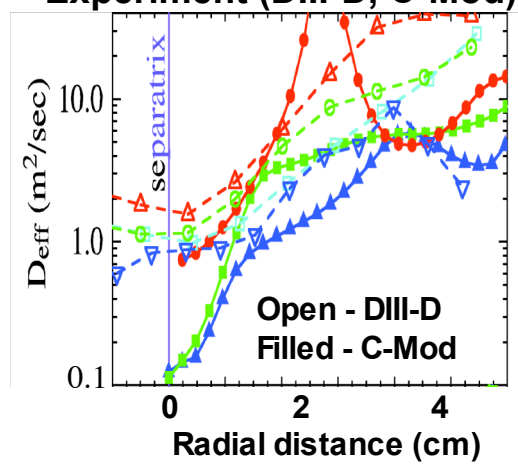
b) Our new coupled results



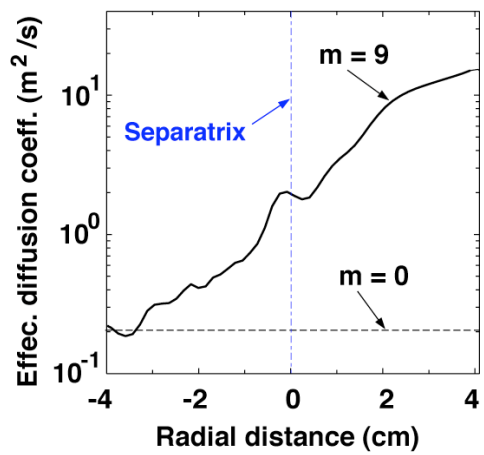
- **Poloidal variation understood from curvature instability**

Results consistent with expt.

Experiment (DIII-D, C-Mod)



Simulated diffusion coeff.

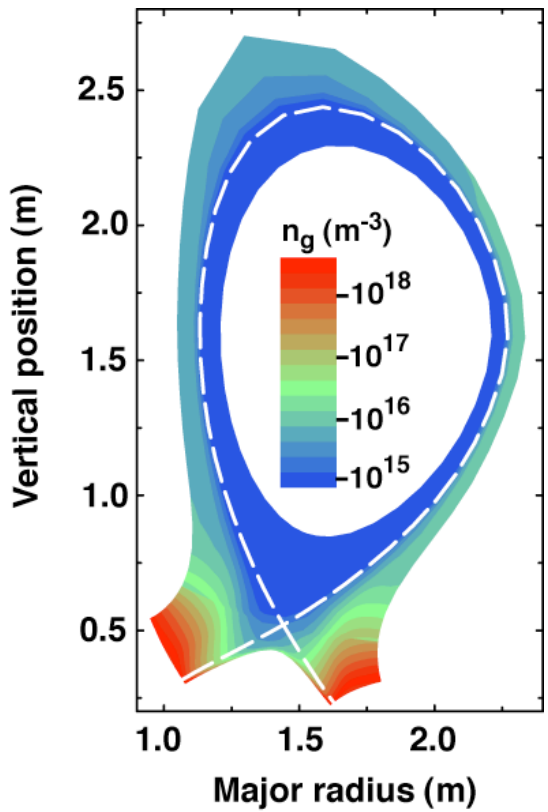


T&T coup

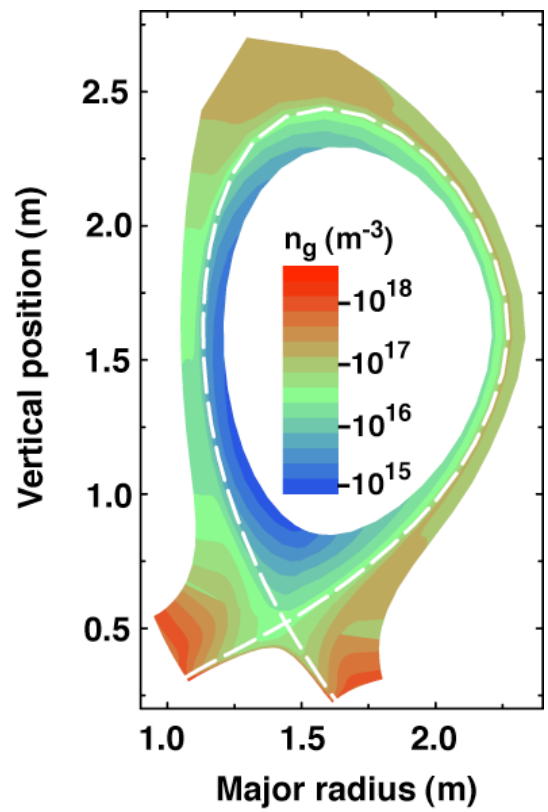
Self-consistent radial transport changes neutral profile via wall/divertor recycling

- With small constant D, divertor recycling strongly dominates
- Self-consistent D from turbulence gives a large wall recycling

a) Neutral density for constant D (m = 0)



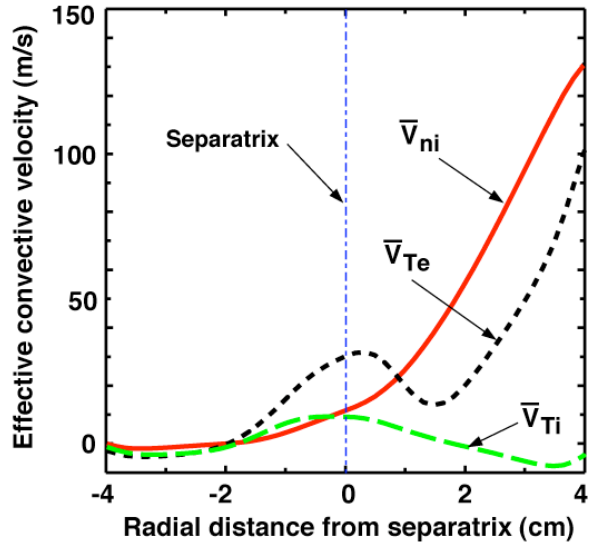
b) Neutral density for turb. D (m = 9)

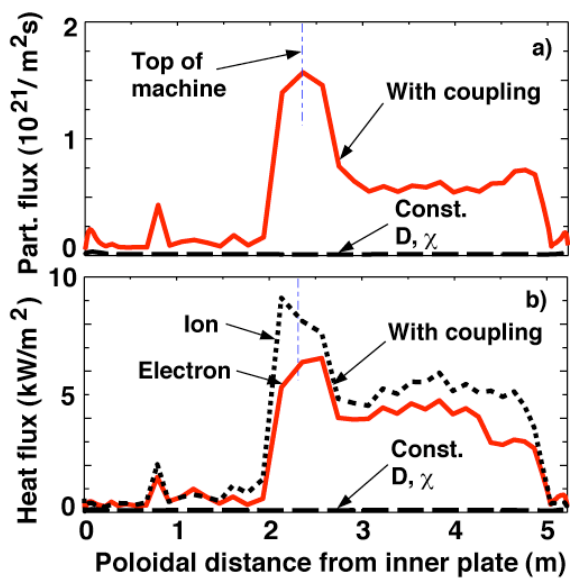


T&T coup

Including T_e and T_i (and $V_{||}$) in coupling shows similar behavior

- Computational work is similar since all nonlinear fluxes are available
- Required splitting transport between convection and diffusion since nonlocal effects appear
- Final convergence hampered by large T_e fluctuations near the wall that cause numerical problems with the turbulence simulation
- Wall fluxes concentrate on outer half; here ~30% goes to wall



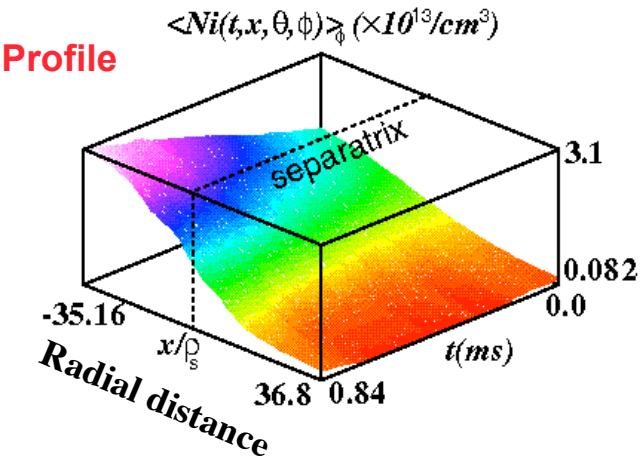


Resolving short-time dynamics involves sometimes using BOUT to evolve profiles

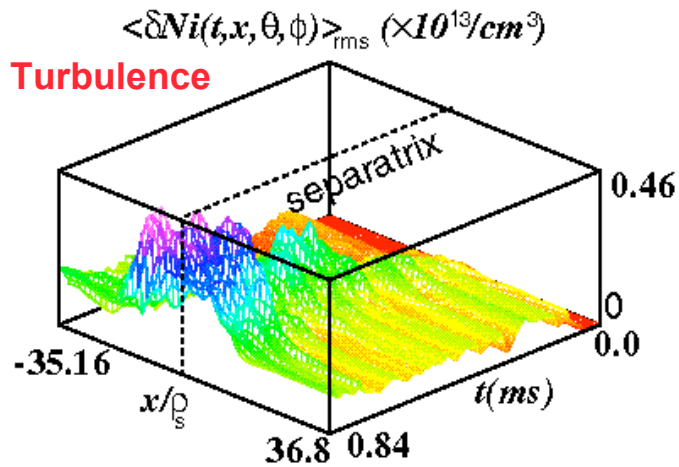
- **BOUT/UEDGE coupling allows long timescale evolution that averages over turbulence - see previous V.G.s**
- **BOUT can be used to evolve profiles for short-time dynamics(e.g., ELMs) - see example on the right**
- **Modeling ELM cycles will utilize a combined strategy**
  - BOUT for ELM crash
  - BOUT/UEDGE for between-ELM profile buildup
  - Cross-checking evolution methods

BOUT density profile evolution at outer midplane

a) Profile



b) Turbulence



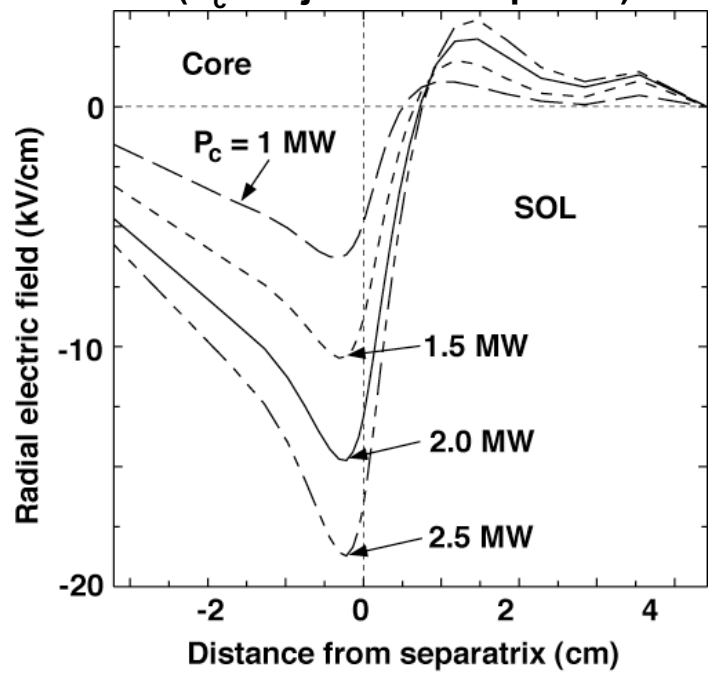
T&T coup

Inclusion of radial electric field is key to generate shear-flow for transport barrier formation

- Low- and high-confinement operation of tokamaks distinguished by $E_r \times B/B^2$ generation of shear flow
- Shear flow can suppress turbulence -> barrier and high edge temperature
- UEDGE and BOUT have similar E_r models that will be included in the coupling

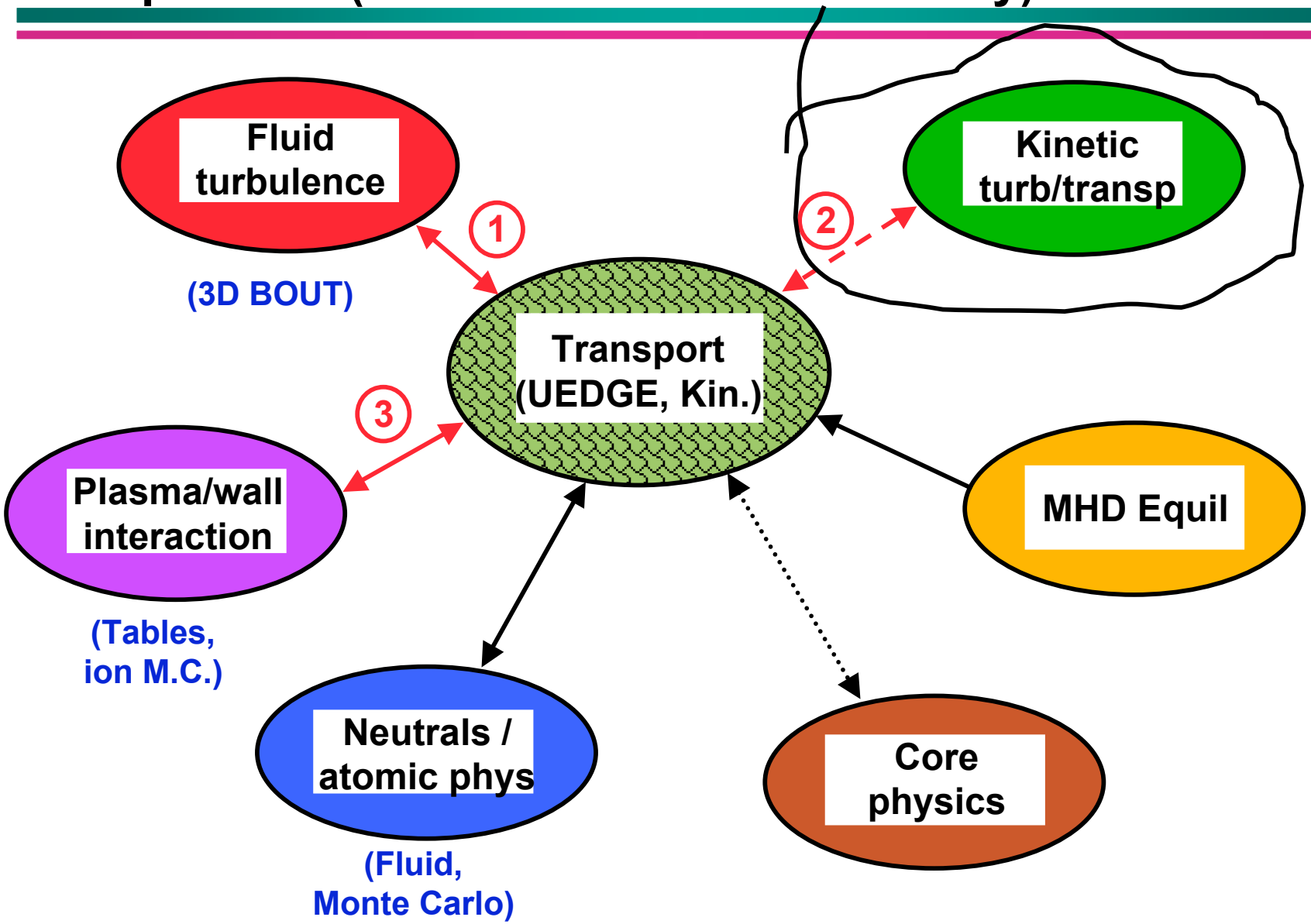
UEDGE models E_r

(P_c = injected core power)



T&T coup

An integrated Edge Module requires many components (red arrows discussed today)



The short mean-free-path fluid regime is not valid in the pedestal region for many H-modes

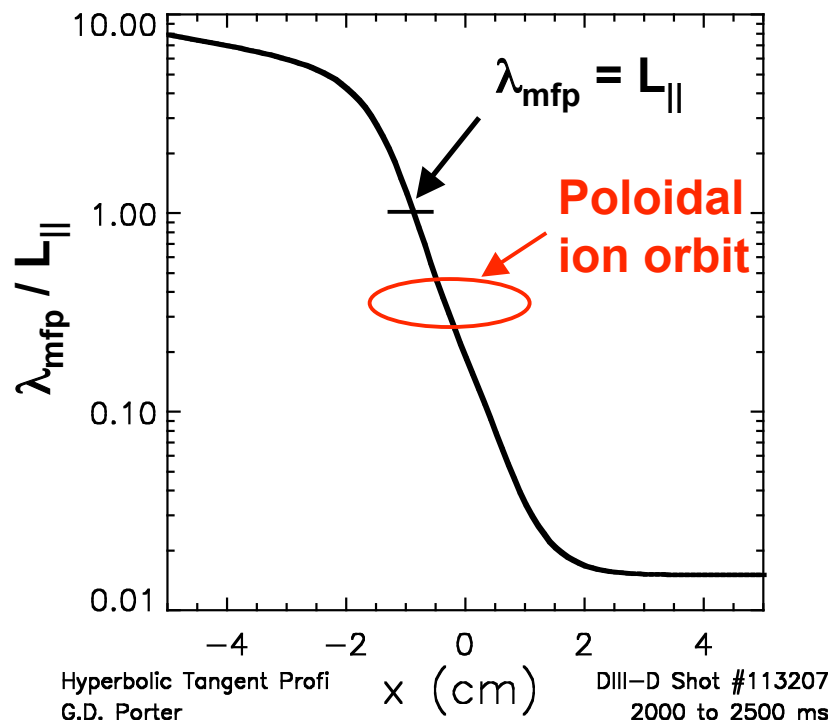
- **Fluid approximation also requires:**

$$\lambda_{mfp} \propto \frac{T^2}{n} > L_{\parallel} \sim 2\pi R$$

(and small poloidal orbit)

- **Not satisfied on DIII-D H-mode, but marginal for Alcator C-Mod**
  - Similarity of edge turbulence suggests fluid models are still relevant (and much faster)

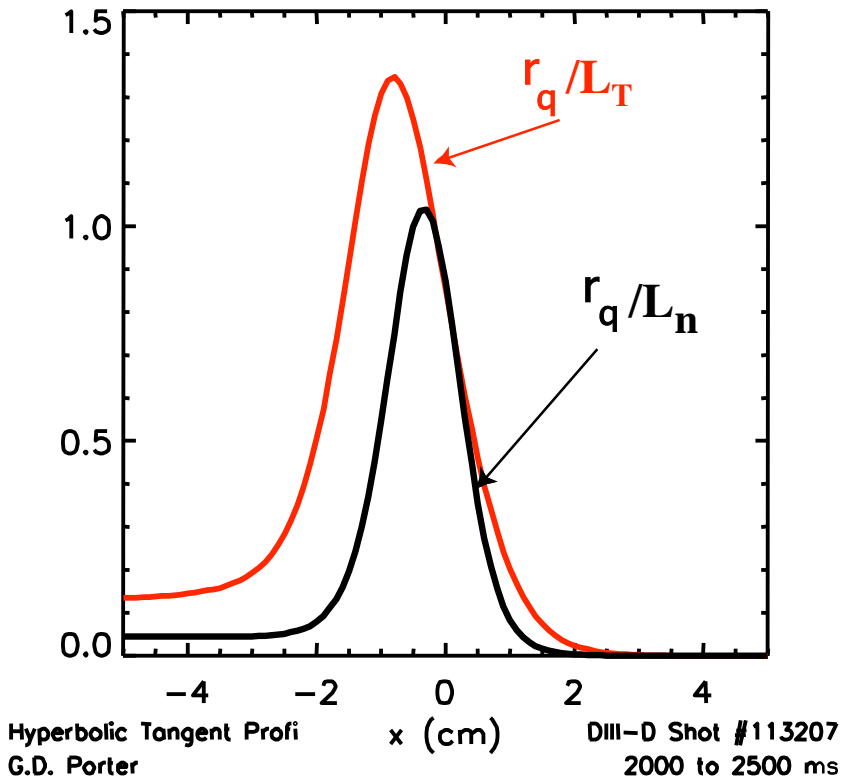
DIII-D Edge collisionality



5D Kinetic

Gyro-kinetic equation must be extended to include steep edge gradients and strong E_r

Gradient lengths ~ r_q for a DIII-D H-Mode



- **A new G-K ordering must obey**
  - $\varepsilon_B = \rho/L_B \sim \varepsilon_\omega = \omega/\Omega << 1$
  - $\varepsilon_p = \rho_\theta/L_p \sim 1$
- **Work is ongoing for new formalism**
  - T.S. Hahm, PPPL
  - H. Qin, PPPL
- **Fokker-Planck collisions also need to be included**
  - A. Brizard

5D Kinetic

Development has thus begun this year on a 5-D continuum gyro-kinetic code (Nevins et al.)

- **A gyro-kinetic average over the fast gyromotion leaves 5 variables for**

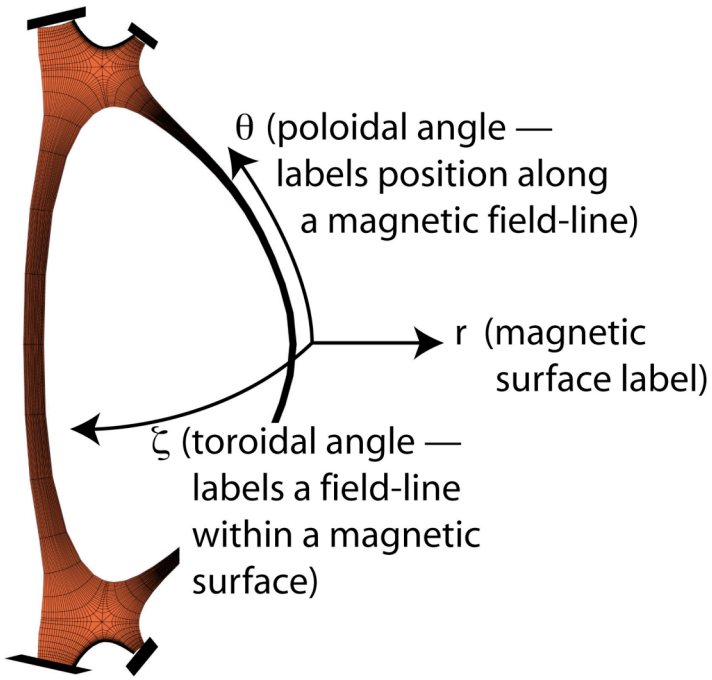
  $F^{(s)}(\varepsilon, \mu, r, \theta, \zeta)$

  coordinates - (energy, magnet. moment, radius, poloidal, toroidal)

- **Initial version this year is 3D**

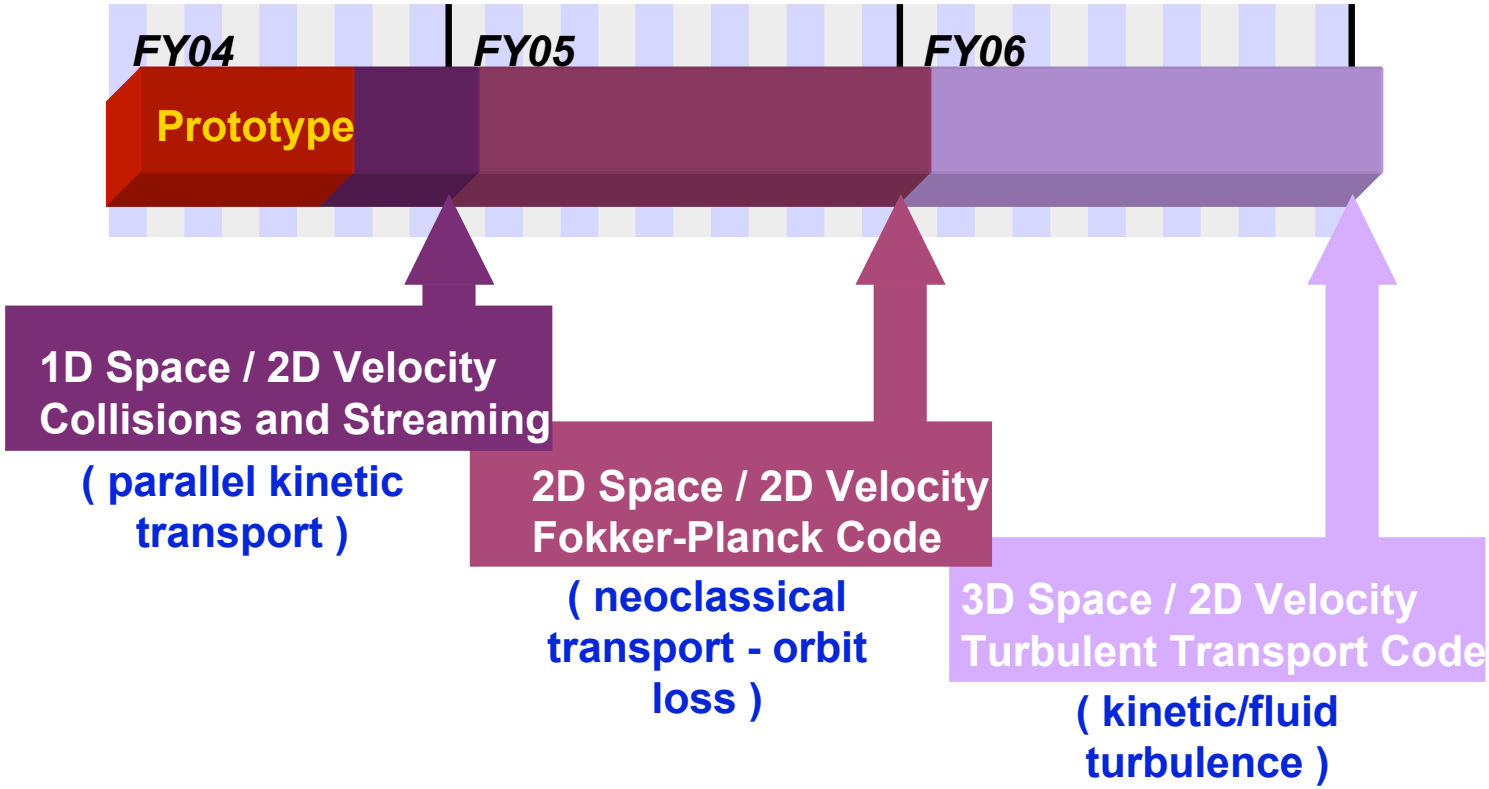
  $F^{(s)}(\varepsilon, \mu, \theta)$

  includes
  - Energy-conserving parallel streaming
  - Fokker-Planck collisions
  - code framework



5D Kinetic

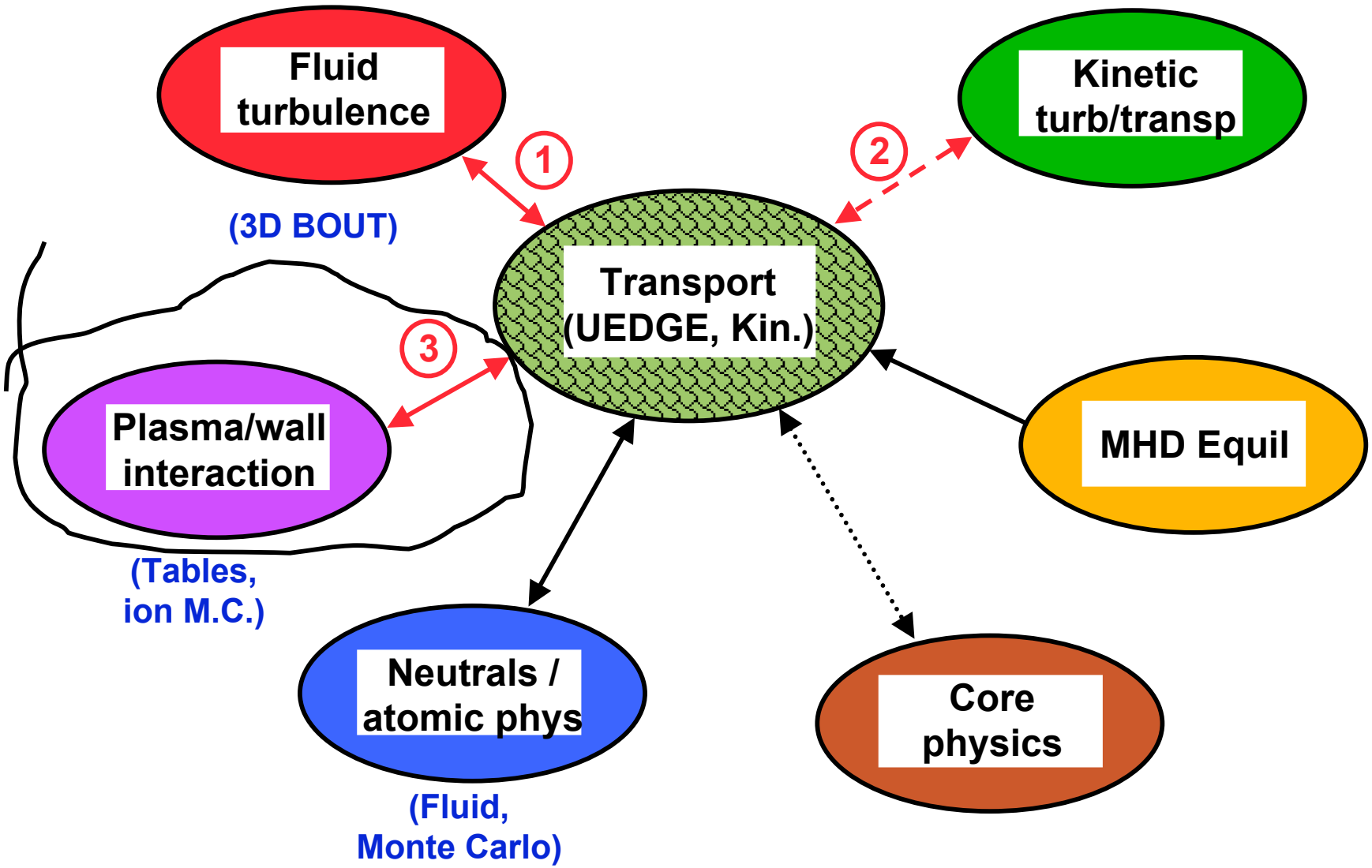
The kinetic code is being developed in stages through FY06



- Initial development being supported by LLNL exploratory funds
- We seek community input and collaborations

5D Kinetic

An integrated Edge Module requires many components (red arrows discussed today)



Joint work with surface & plasma groups is providing a model of edge plasma impurities

Impurities in the edge plasma are important for power balance

Widely varying length scales

~ nm

~10 cm

~10 m

Carbon plate MD and kinetic MC simulations for sputtering

Output

Multi-parameter table for C, CH_4 sputtering yield

Plasma flux

Near-surface carbon plasma transport and chemistry for C transfer rate

(e.g., WBC)

Output

Multi-parameter table for transfer from CH_4 to C

DT plasma

Multi-charge state C-ion fluid transport in whole edge region

Output

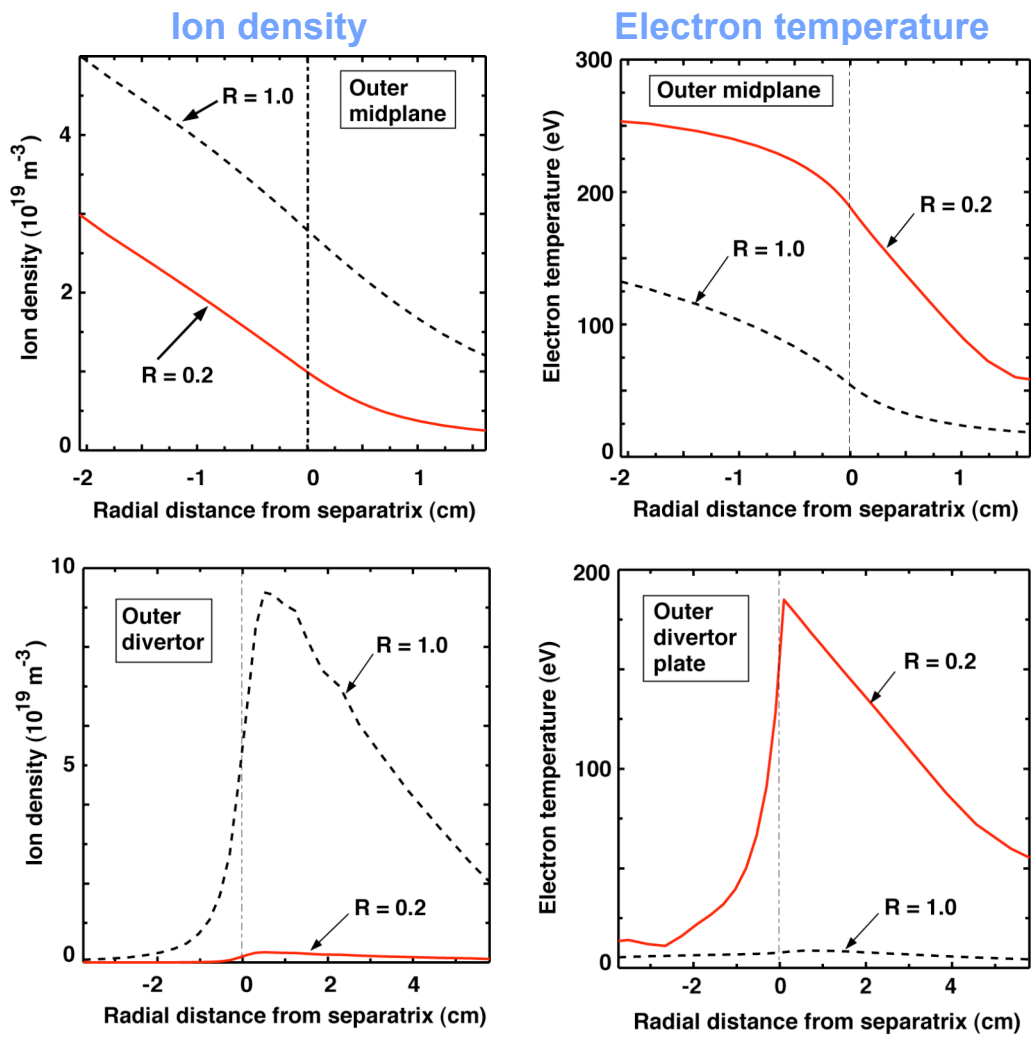
C-ion charge-states in edge coupled to GK code

Surface pla

NSTX with Li divertor surface: Low recycling increases midplane temperatures by factor of ~2

- Low recycling decreases edge density for fixed source
- For R=0.2, $\lambda \sim L_{||}$
- Sputtering increases for low recycling (high T_e)

Increased edge temperature often reduces core turbulence

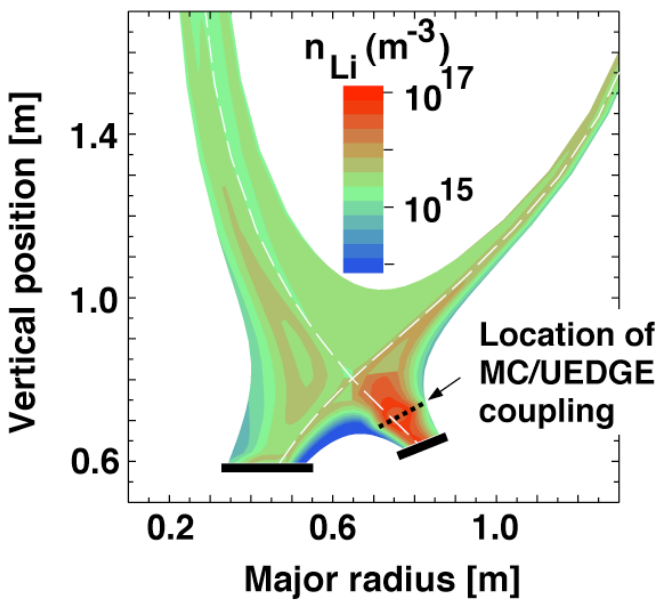


Surface pla

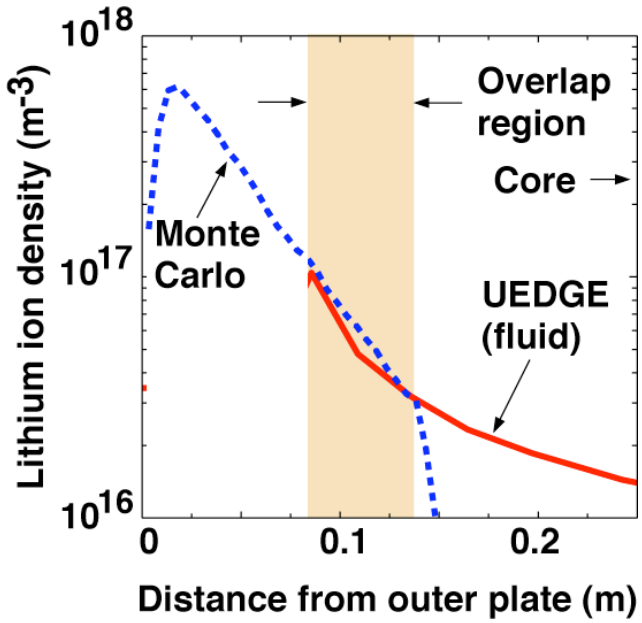
Ion Monte Carlo code (WBC) provides the Li impurity source for UEDGE to assess impact on NSTX

Other impurities (e.g., C) can be modeled similarly to Li example below

Calculated Li impurity density



WBC ion M.C. and fluid codes overlap



J. Brooks et al., PSI, 2004 - JNM

1. UEDGE provides the hydrogen plasma background
2. Near-surface plasma chemistry code provides the impurity source
3. UEDGE computes impurity concentration throughout edge

Surface pla

Summary

- **Coupling fundamental fluid turbulence with transport**
  - Demonstrated for four variables (n_i, $v_{i||}$, T_e, T_i) and neutrals
  - Being extended to E_r (potential) and time dependence

- **Continuum edge kinetic code being developed**
  - Fall '04 - 3D: 2 velocities and 1 spatial dimensions
  - Fall '05 - 4D: 2 velocities, 2 spatial dimensions - transport
  - Fall '06 - 5D: 2 velocities, 3 spatial dimensions - turbulence

- **Iterating near-surface ion M.C. sputtering/transport with whole-edge transport indicates Li can be retained in NSTX divertor**