Edge-plasma modeling: UEDGE, edge turbulence, and kinetic effects*

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- R. Groebner, GA

Some of what you should know above edge/PMI modeling - an outline

- **Impressive features of fluid transport modeling (UEDGE, …)**
  - complex magnetic geometry
  - multispecies impurity transport/radiation
  - neutral transport/sources
  - wall sputtering/recycling/re-deposition
  - partial fitting of experimental data

- **Limitations and emerging improvements**
  - physics-based turbulent radial transport (D, V, χ; blobs; ELMs)
  - kinetic plasma effects – parallel perpendicular to B-field
  - integrated/self-consistent edge/wall and edge/core coupling
  - toroidal (3D) asymmetries, peaking factors

Edge transport modeling has primarily used fluid equations obtained by moments of kinetic eqn.

- Continuity and momentum equations are solved for plasma & neutrals

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

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

<u>Similar energy equations solved for T_e and T_i</u>

- Radial velocities are convective-diffusive (fit) + classical drifts

Turbulence Classical

$$V_r = V_{conv} - D(dn_k/dr)/n_k + ExB/B^2 + V_{grad\ B}$$

- Turbulence fit or from simulation; parallel transport classical
- Parallel electron thermal conduc. timescale ($\leq 10^{-7\text{-}8}$ s); implicit solver
- Electrostatic potential from $\nabla \bullet J = 0$

Fusion Energy Program

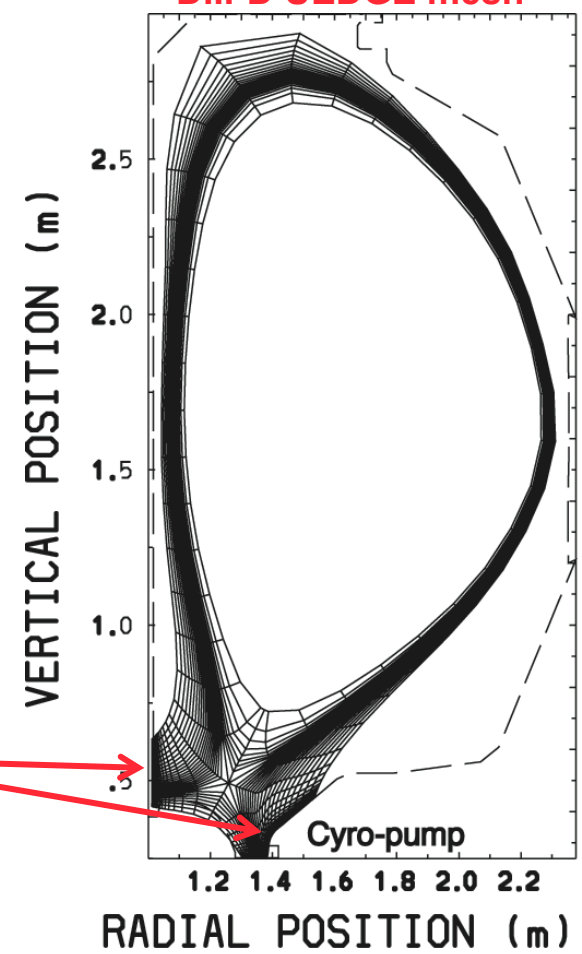
UEDGE is a 2D plasma/neutral fluid transport code covering closed & open field-line regions

- **Features of UEDGE**

  Physics:
  - Multispecies plasma; var. $n_{i,e}$, $u_{||i,e}$, $T_{i,e}$, ϕ
  - Flux-limited kinetic corrections
  - Fit radial plasma transport coefficients or coupling to BOUT turbulent fluxes
  - Reduced Navier-Stokes or Monte Carlo for wall-recycled/sputtered neutrals
  - Multi-step ionization and recombination

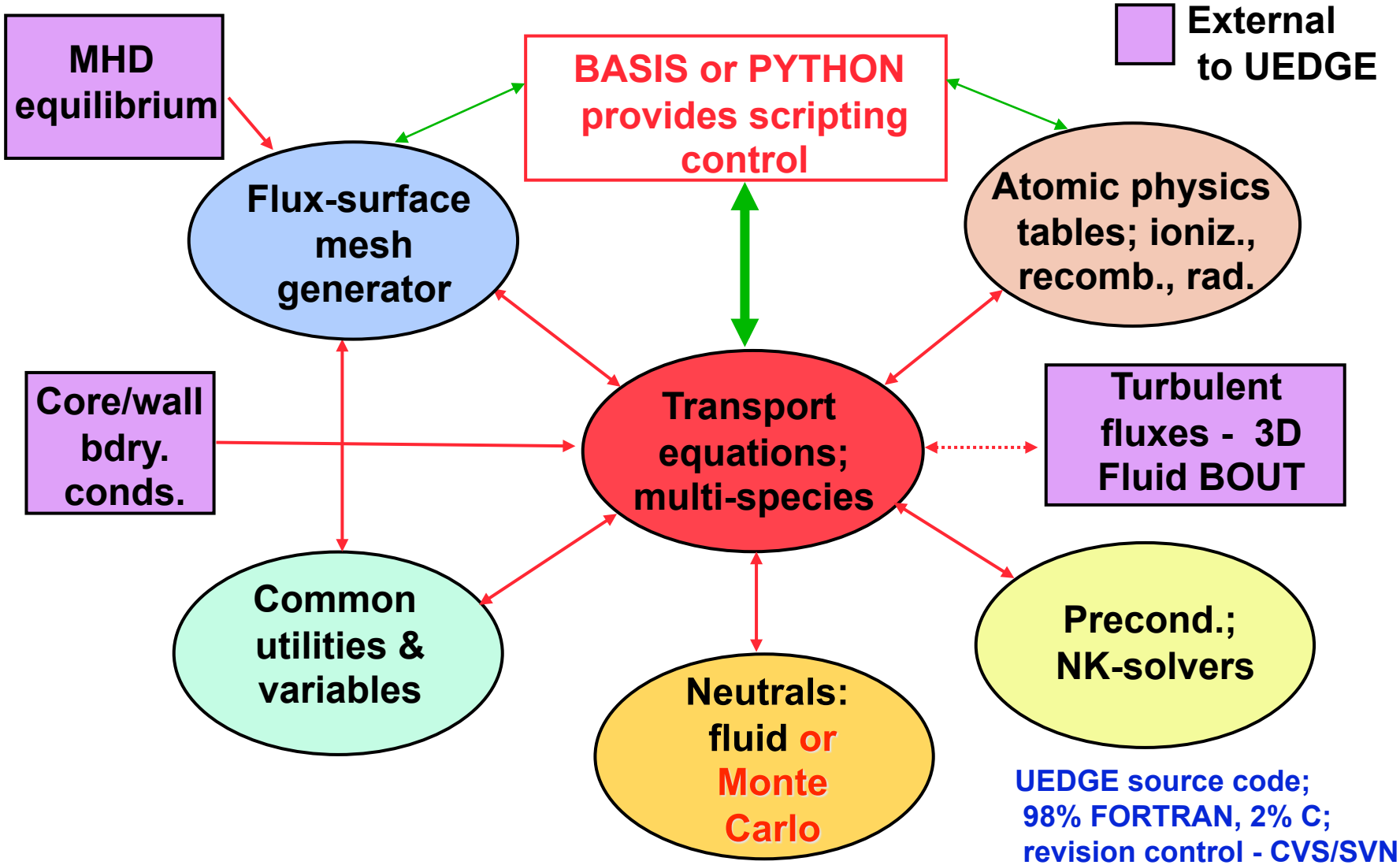
  Numerics:
  - Finite Vol.; Newton-Krylov implicit solver
  - Non-orthogonal mesh for fitting divertor
  - Steady-state or time dependent
  - Parallel version with 2D decomposition
  - PYTHON or BASIS scripting control

DIII-D UEDGE mesh



Fusion Energy Program

UEDGE is built in a modular fashion

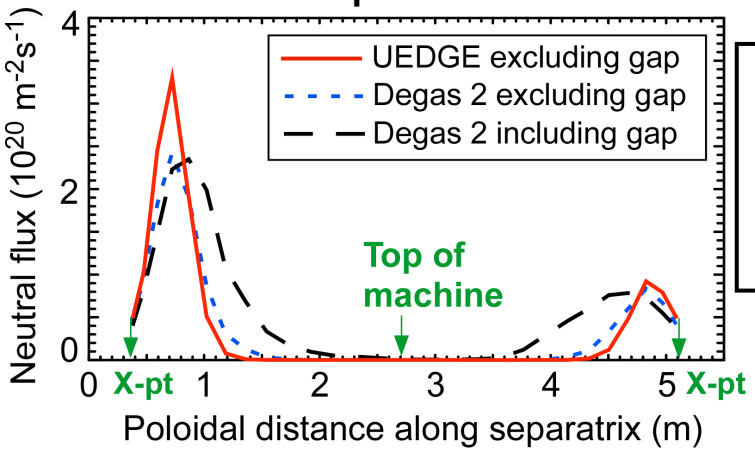


UEDGE source code;
98% FORTRAN, 2% C;
revision control - CVS/SVN

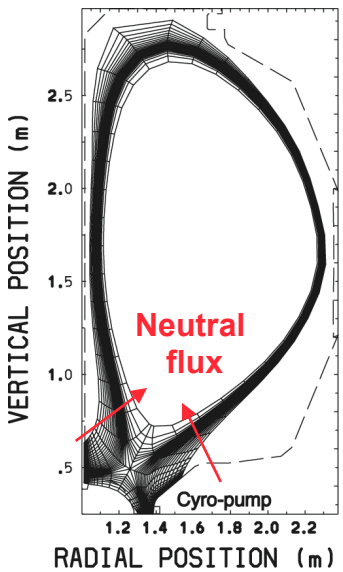
Fusion Energy Program

Recycled neutrals usually dominate fueling; pedestal structure impacted - fluid and Monte Carlo similar

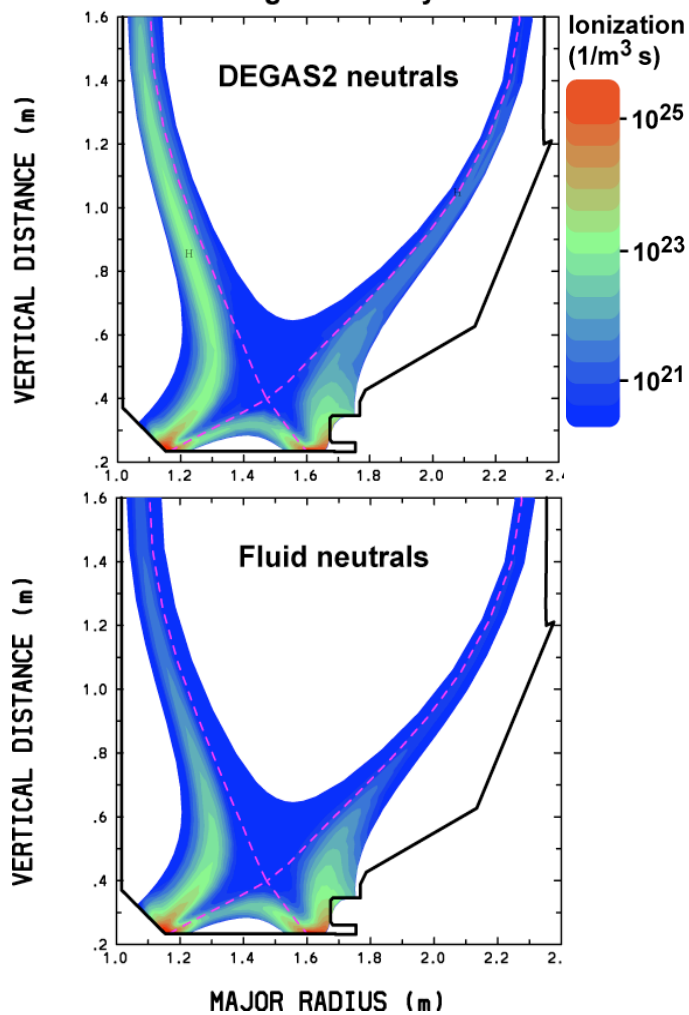
Radial neutral fueling-flux across separatrix in DIII-D



Gap region is beyond normal UEDGE mesh

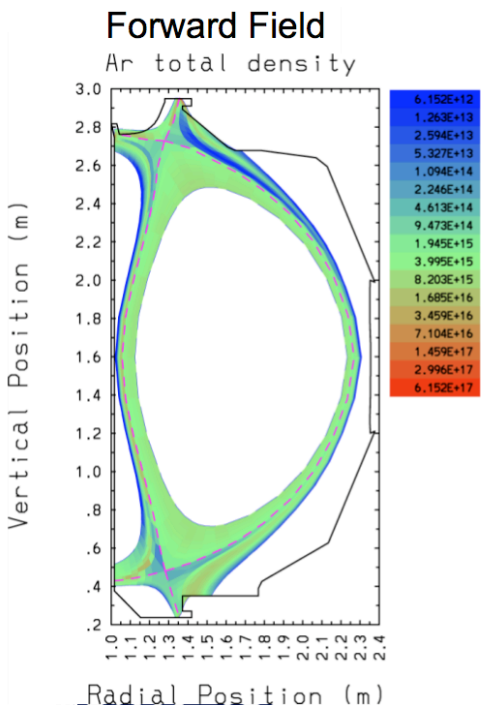


ELMy H-mode, higher density



Fusion Energy Program

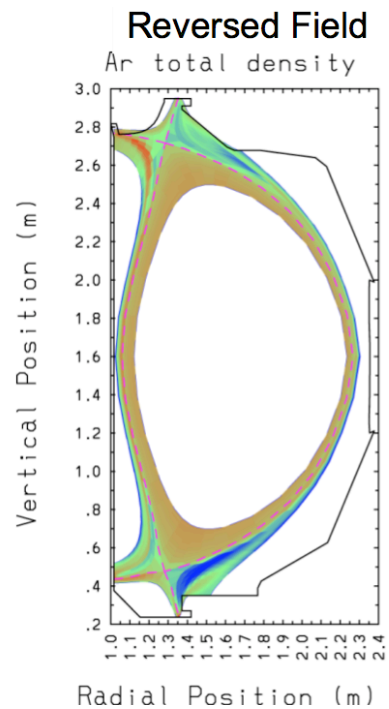
Classical ExB and grad_B drifts are important for argon transport into the core plasma of DIII-D (Porter)

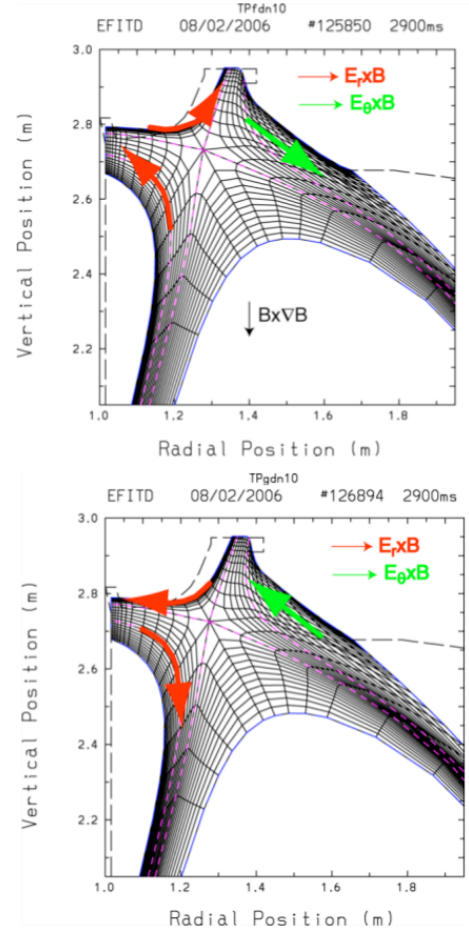


Core Ar ion density is 6.6 times higher for reversed field

Ratio is about 4 experimentally

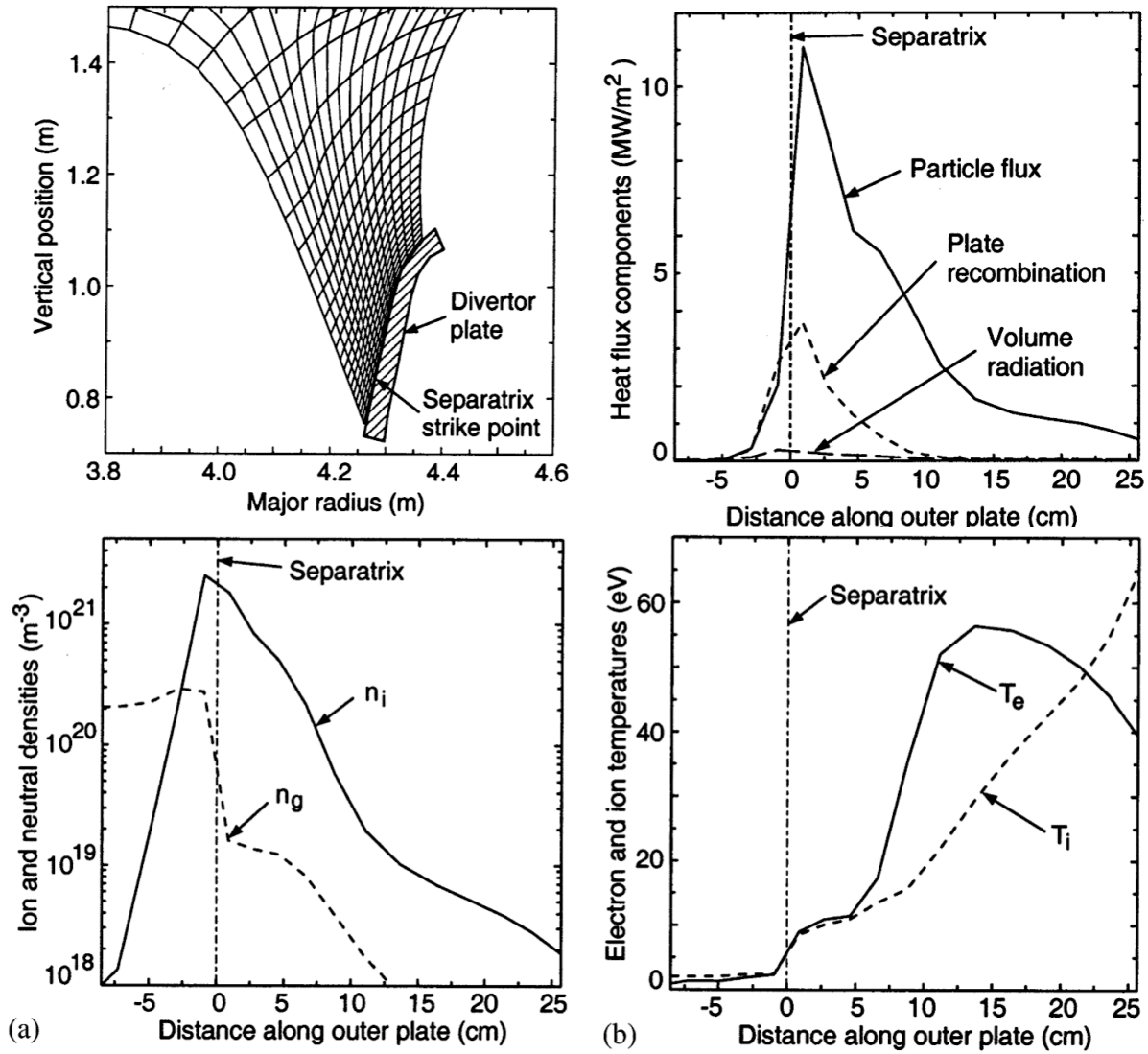
Core Ar in DN is 2–4X that in USN, comparable to experiment





Fusion Energy Program

We have done some basic modeling of some ARIES tokamak designs (e.g., AT, RS) for divertor heat-flux



Large mantle radiation loss 77% assumed here

Rognlien, Rensink, Fusion Eng. Design, **60** (2002) 497.

Fusion Energy Program

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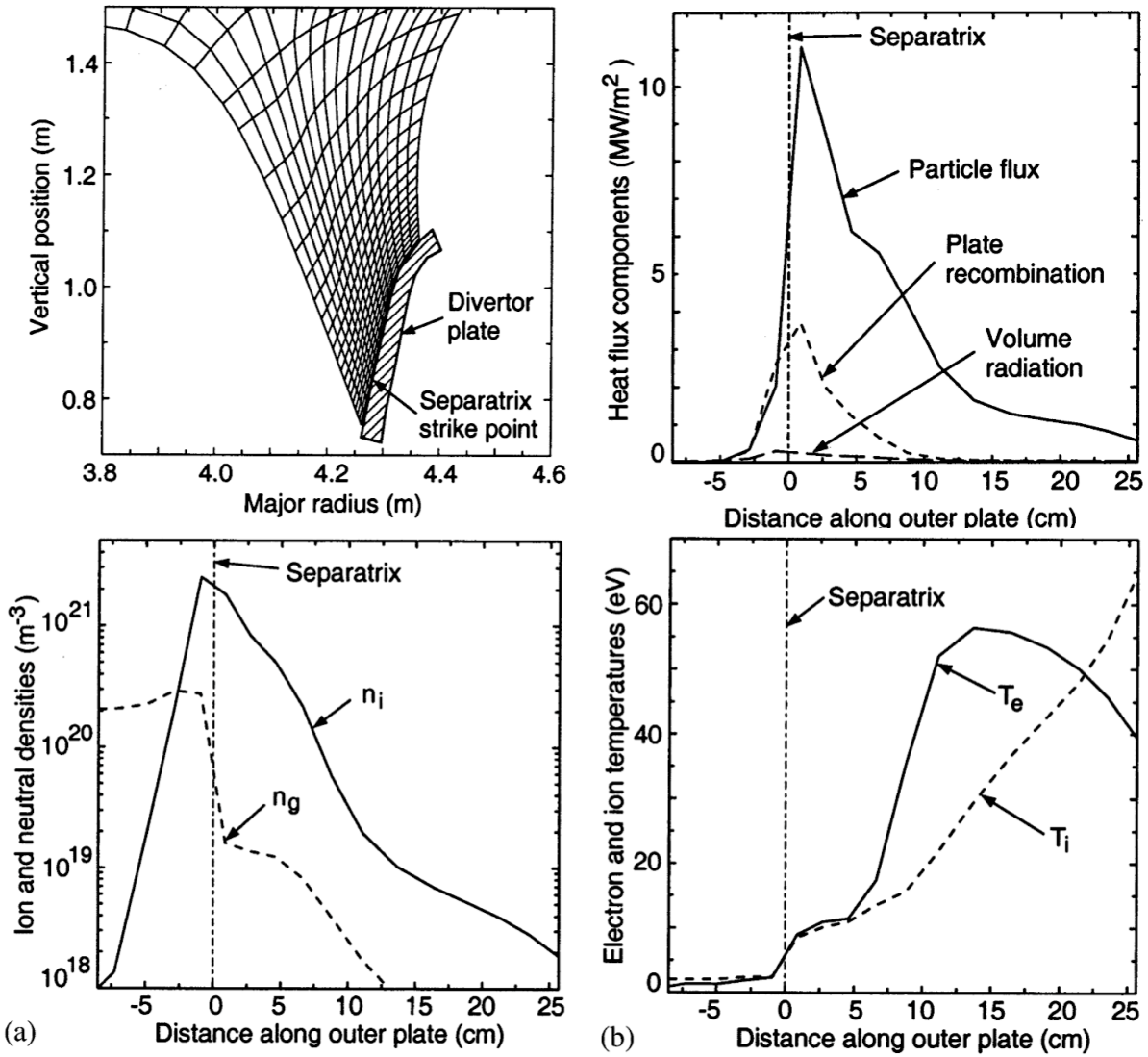

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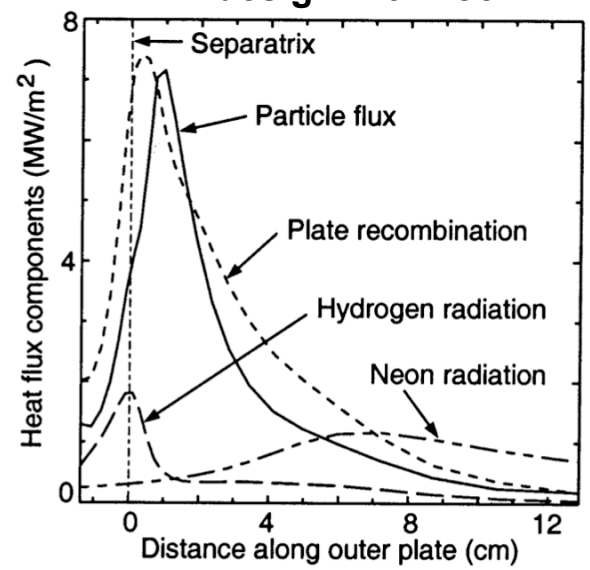
FIRE design with neon



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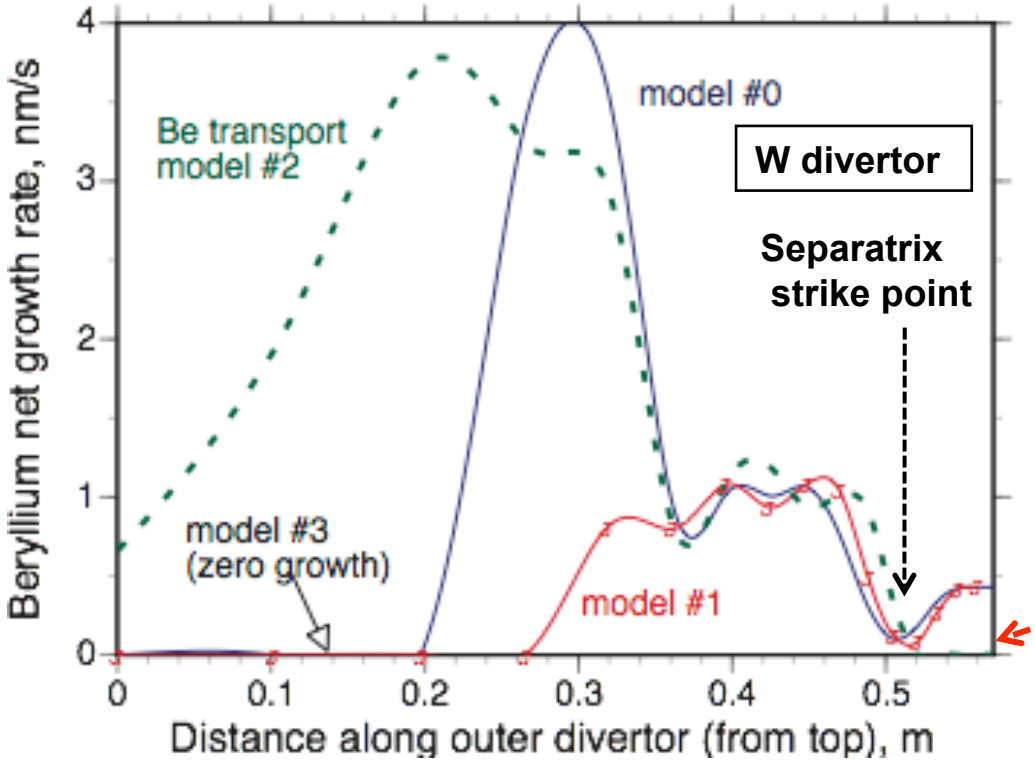
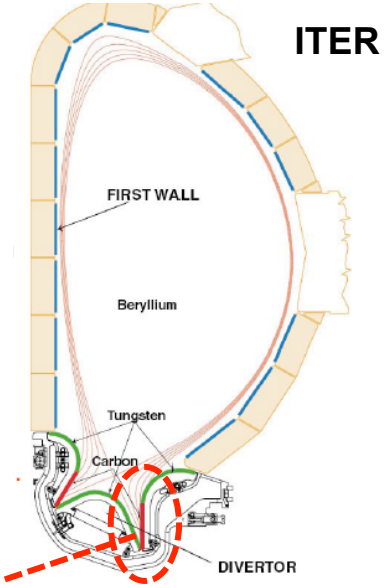
Fusion Energy Program

UEDGE DT fluxes sputter Be from ITER wall; couple Be to WBC code (Brooks) models divertor plate deposition





Transport Model #	Plasma (D-T) Edge Transport	Wall-Sputtered Material Transport
0	With convection*	No convection
1	"	Same as plasma
2	"	-modified Pigarov et al. model**
3	No convection; diffusion only	No convection; diffusion only

Be growth on divertor ranges from zero to significant, depending on transport model.

Fusion Energy Program

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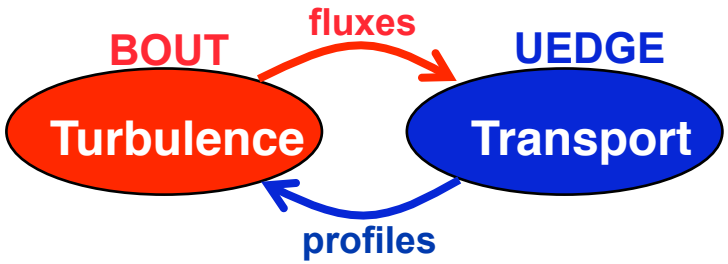
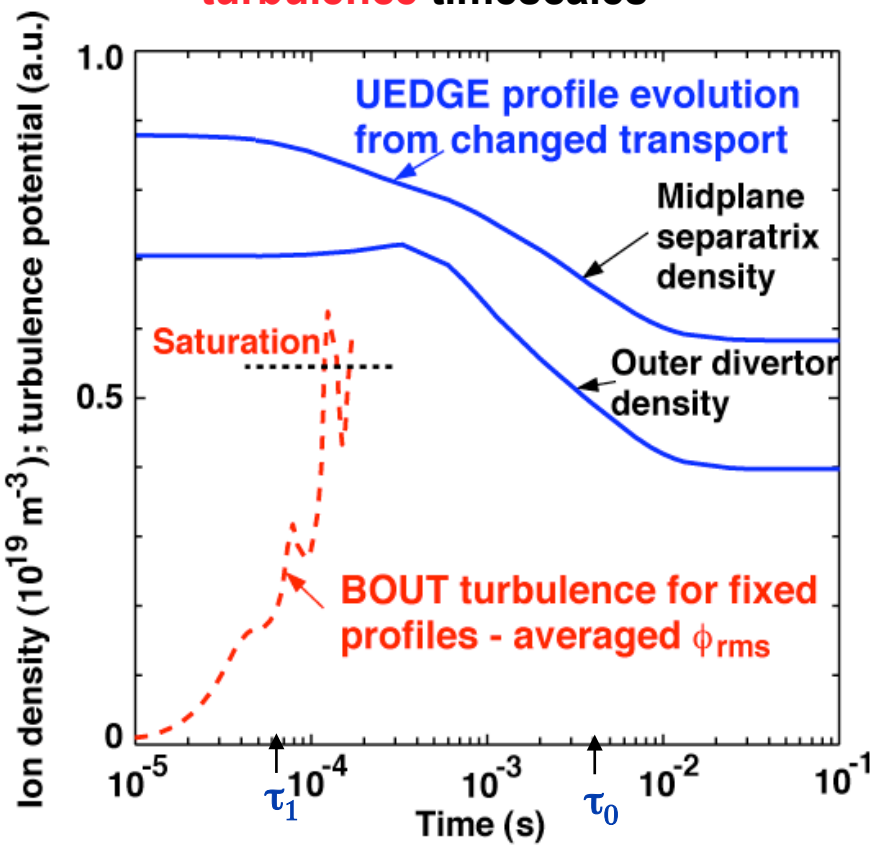
Fusion Energy Program

Turbulence and transport equilibrium exhibit widely different characteristic time scales



- BOUT is 3D plasma turbulence code; UEDGE is 2D plasma/ neutral transport code
- Within the iterative coupling scheme, the BOUT turbulence is evolved for τ_1 ~ 50-100 μs
- During the same iteration step, UEDGE takes a larger time step, with τ_0 > 10 ms
- Resulting final state is thus a statistical steady-state

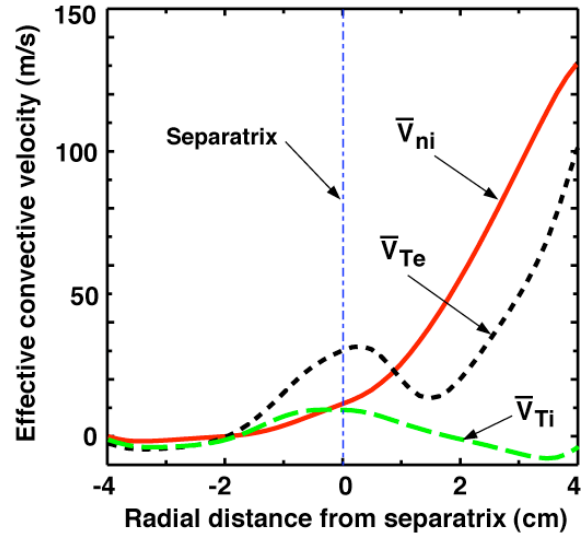
Comparison of transport and turbulence timescales

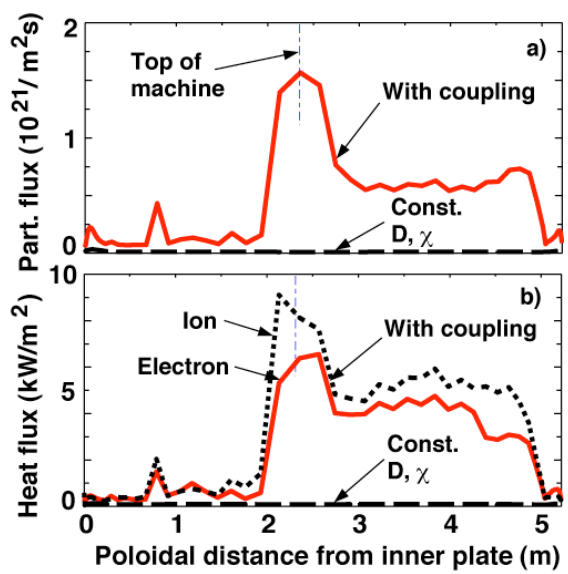


Fusion Energy Program

Including n_i, $V_{||}$, T_e, and T_i (and $V_{||}$) in turbulence/transport coupling shows strong outward convection (blobs)

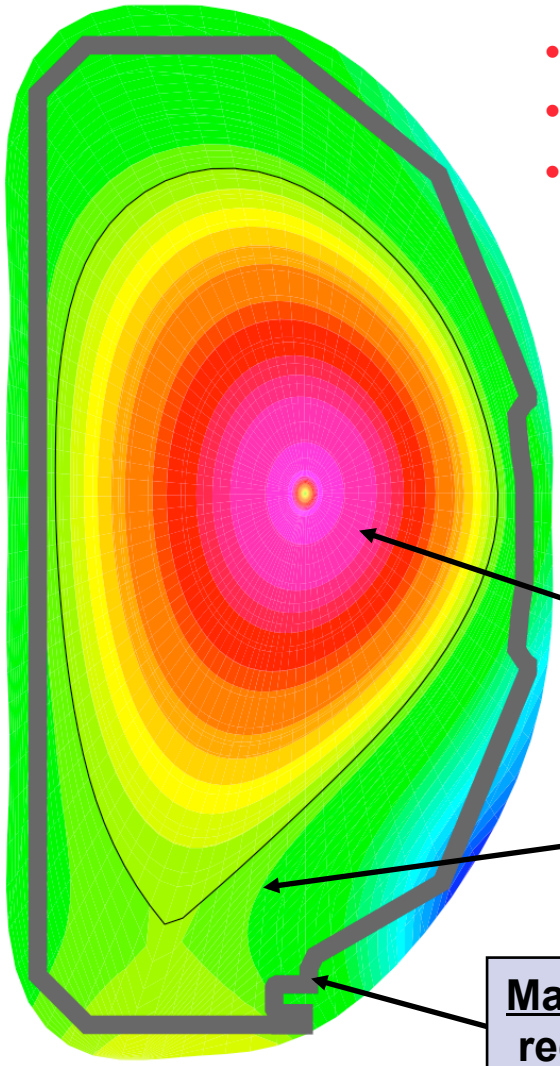
- Computational work is similar since all nonlinear fluxes are available
- Required splitting transport between convection and diffusion since nonlocal effects appear
- Final convergence hampered by large T_e fluctuations near the wall that cause numerical problems with the turbulence simulation
- Wall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





Fusion Energy Program

FACETS goal: a tight-coupling framework for core-edge-wall (John Cary, PI)



- Provides demonstrated framework
- Coupling on short time scales; implicit possible
- Inter-processor and in-memory communication; highly parallel

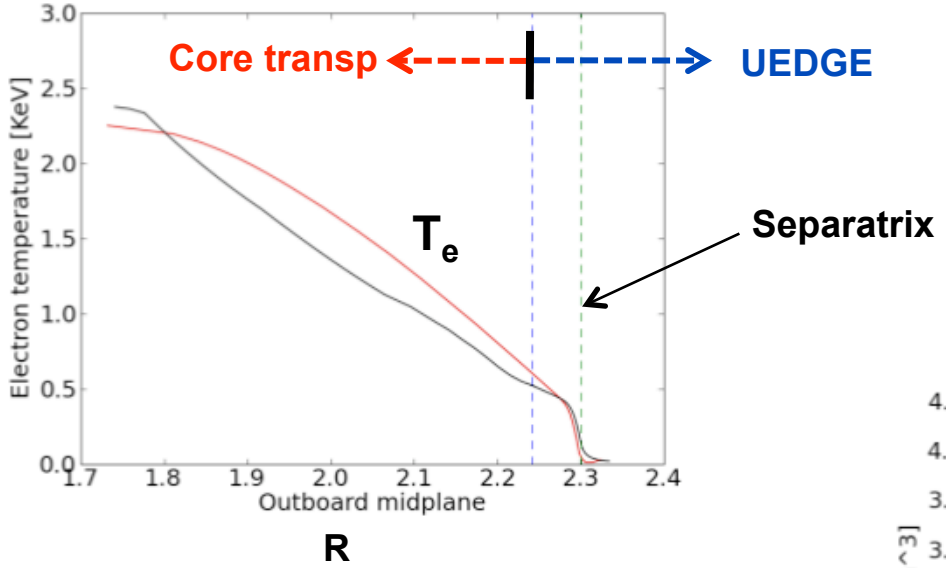
Hot central plasma: nearly completely ionized, magnetic lines lie on flux surfaces, 3D turbulence embedded in 1D transport

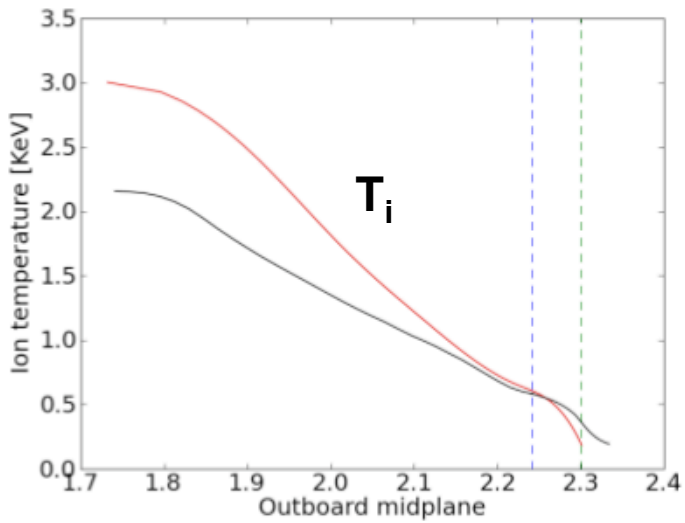
Cooler edge plasma: atomic physics important, magnetic lines terminate on material surfaces, 3D turbulence embedded in 2D transport

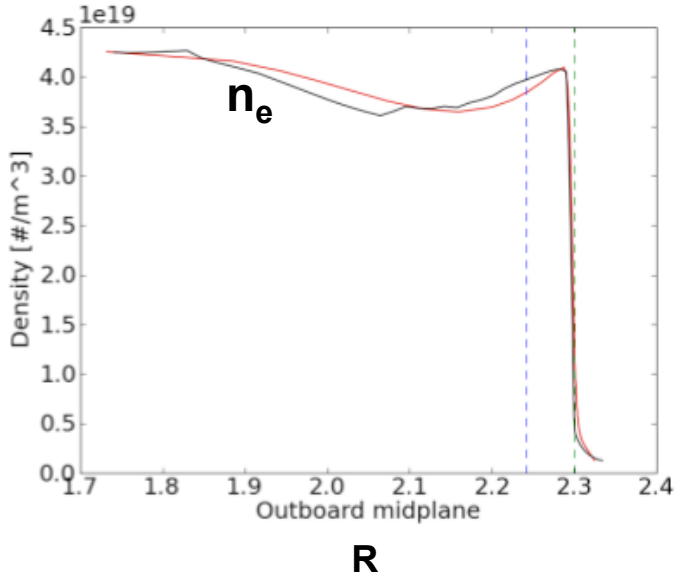
Material walls: trapped hydrogenic species, recycling, sputtering

Fusion Energy Program

In-progress FACETS core/edge/SOL coupling for DIII-D shot 118897 (Hakim et al.); 35 ms; preliminary!



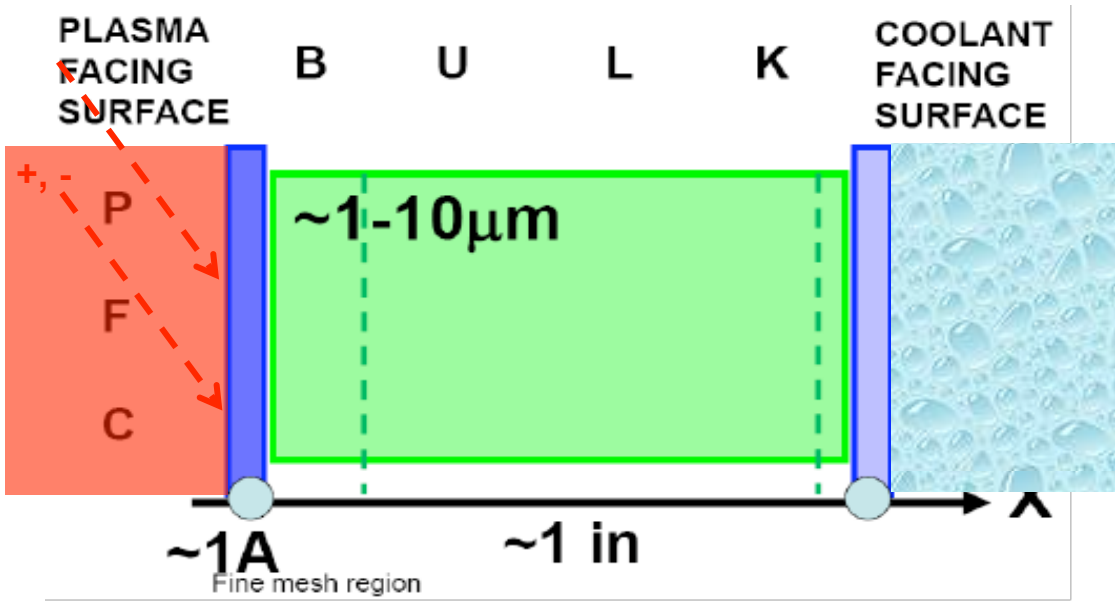




Fusion Energy Program

WallPSI is a 1D material response code being developed at UCSD (Pigarov et al.)

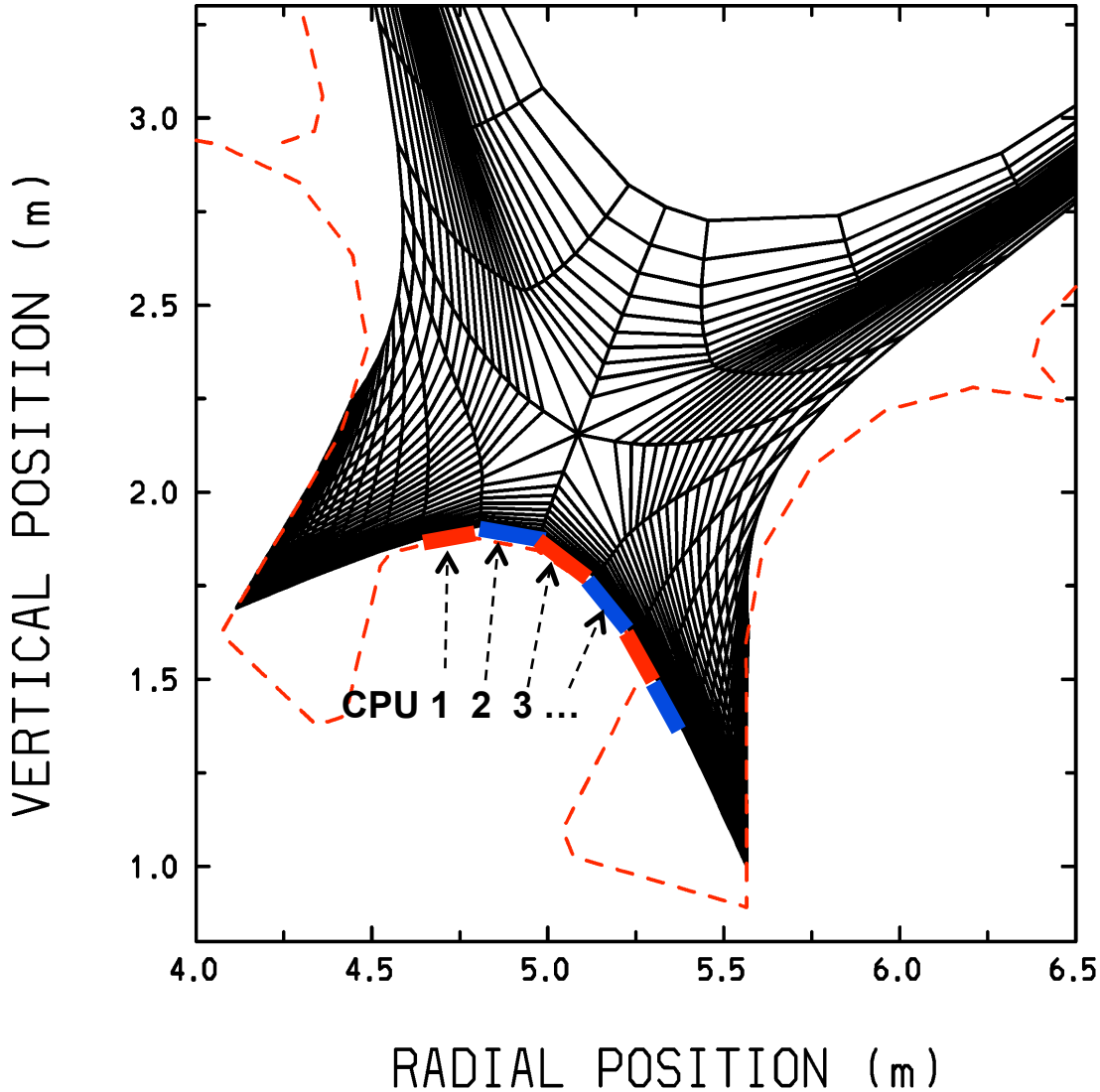
- **Continuum code to simulate time-dependent 1-D transport of plasma particles and heat in the wall**
  - Modeling wall segment includes: 1-D bulk and 0-D plasma facing surface (PFS) and coolant facing surface (CFS)
  - Distinguish mobile, adsorbed, and trapped hydrogen on surfaces / in bulk
  - Wall segment covered with a non-uniform mesh with 1-A resolution near surfaces
  - Multiscale: shortest time < 1 ns; largest time > 1 year bulk diffusion, permeation



Fusion Energy Program

Independent 1D wall modules connected to each UEDGE wall/divertor cell

- Framework is in place; working for core /edge
- Each wall module can run on different processors; ~100 CPUs
- Most links are in place – test this summer



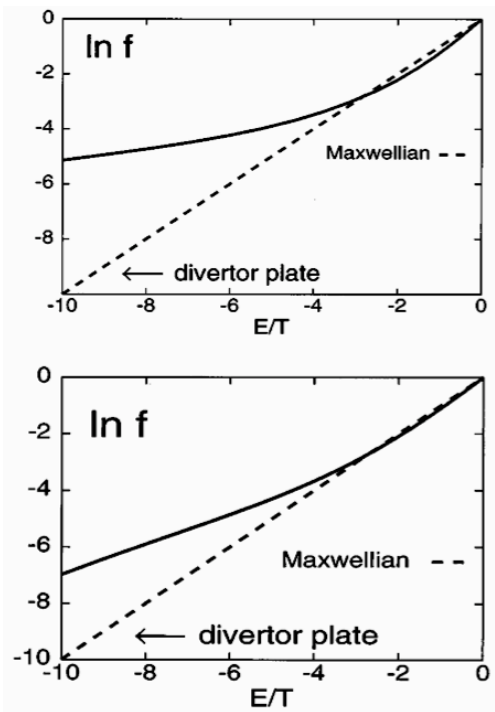
Fusion Energy Program

Emerging 4D and 5D edge kinetic codes will provide powerful tools to assess kinetic effects

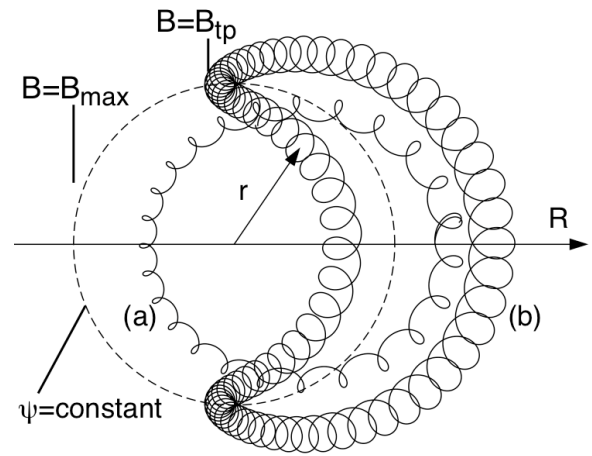
Edge kinetics gives

- continuous transition from long to short mfp along & across B
- steep gradients allowed
- strongly sheared ExB
- $k_\perp \rho_i \geq 1$ and Landau damping for turbulence
- large fluctuations

1D-2v Fokker-Planck Batishchev et al. '97 show parallel kinetics



Passing/trapped orbits, if weakly collisional on a banana bounce time



$\Delta r = 2v_{||} / \omega_{cp}$

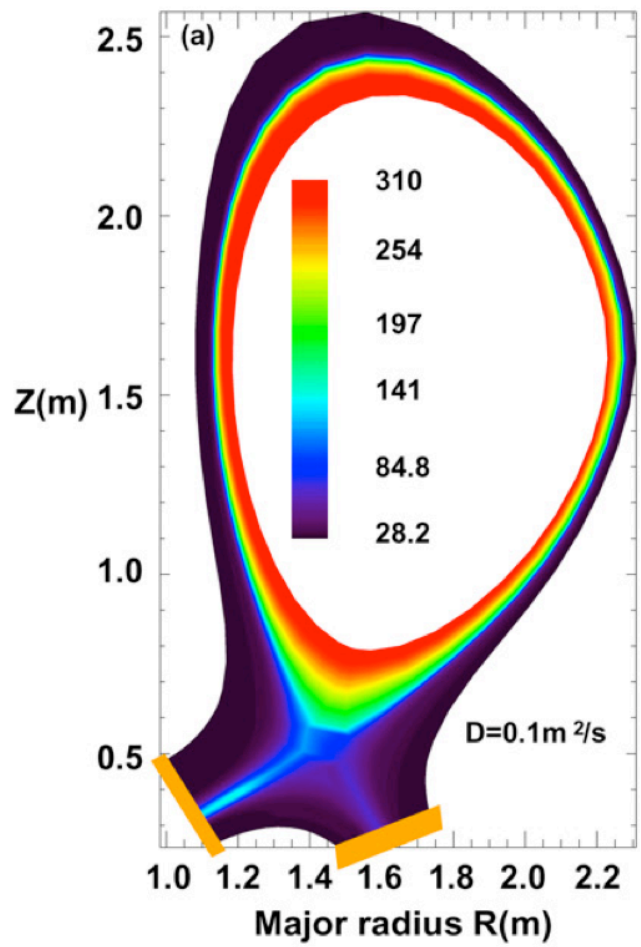
Gyrokinetic equation implemented in ESL continuum TEMPEST/COGENT/NEO; CPES has XGC0,1 – PIC codes

$$
\begin{aligned}
\frac{\partial F_\alpha}{\partial t} &+ \bar{\mathbf{v}}_{\mathrm{d}} \cdot \nabla_\perp F_\alpha + (\bar{v}_{\|\alpha} + v_{Banos}) \nabla_\| \partial F_\alpha \\
&+ \left[q \frac{\partial \langle \Phi_0 \rangle}{\partial t} + \bar{\mu} \frac{\partial B}{\partial t} - \frac{qB}{B^*} \bar{v}_\| \nabla_\| \langle \delta\phi \rangle - q \mathbf{v}_{\mathrm{d}}^0 \cdot \bar{\nabla} \langle \delta\phi \rangle \right] \frac{\partial F_\alpha}{\partial E_0} \\
&= C(F_\alpha, F_\alpha),
\end{aligned}
$$

- GK F-equation discretized with high order (4th); Fokker -Planck collisions
- Gyrokinetic Poisson eqn solves for electrostatic ϕ
- Porting to Chombo; full-f and δf options available
- Circular & divertor geom.; 2D equilibrium potential
- Runnable as
  - 4-D for transport with $F(\Psi,\theta,\varepsilon,\mu)$, or
  - 5-D for turbulence with $F(\Psi,\theta,\phi,\varepsilon,\mu)$ – beginning

Hot ion component

T_i (eV)



Fusion Energy Program

Summary

- **Edge plasmas have a major impact on both core fusion yield (via pedestal structure) and on the survivability of PFCs**

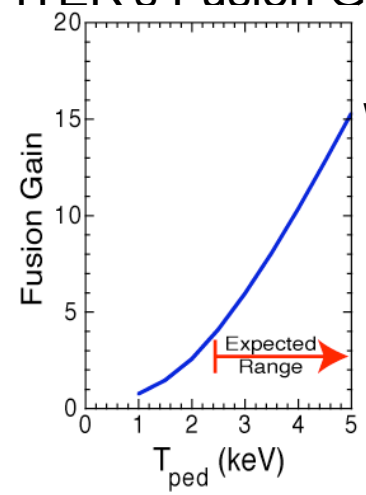
- **Present transport modeling includes many effects**
  - geometry; plasma flux to PFCs; neutrals; impurities; radiation
  - predictability is largely empirical at best

- **Filling the gaps**
  - turbulence transport simulations; long-time coupling
  - kinetic plasma transport for hot edge plasmas
  - integration of core/edge/wall
  - toroidal (3D) asymmetries, peaking factors

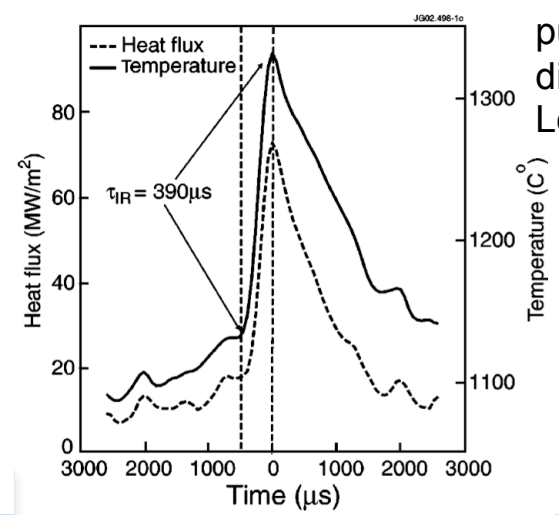
Many key fusion issues relate directly to the behavior of edge plasmas

- **Key Burning Plasma issues**
  - Understand dynamics of edge Pedestal region
  - Physics and control of Edge-Localized Modes
  - Stabilization of neoclassical tearing modes
  - Develop s.s. & advanced tokamak regimes
  - Density limit and high density operation
  - Turbulence and transport
  - Disruption avoidance and mitigation
  - Diagnostics of burning plasmas
  - Plasma facing components and tritium interactions
  - Divertor Science & Technology development
  - Tritium breeding blankets

Projection of ITER's Fusion Gain



Waltz et al, '02; Kinsey, '03

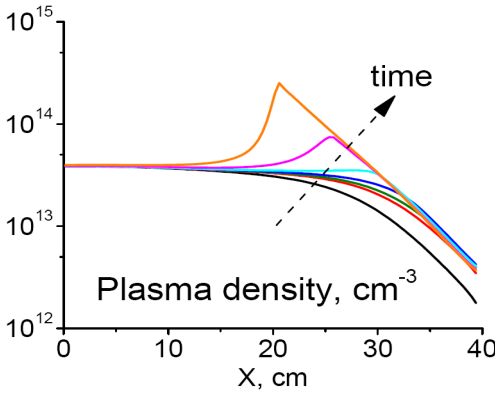


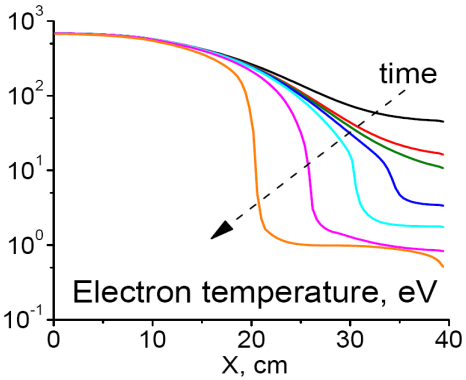
ELM heat pulse to JET divertor; Loarte '04

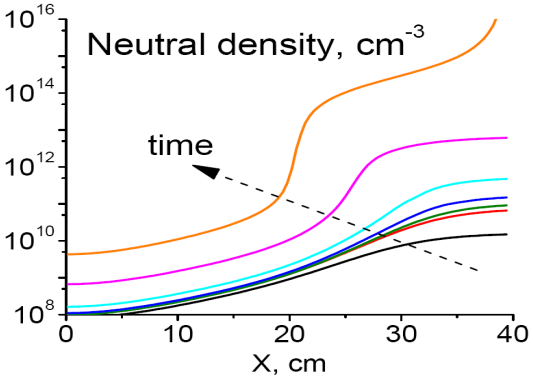
Fusion Energy Program

Initially WallPSI coupled to simple 1D plasma model for preview of important transient effects

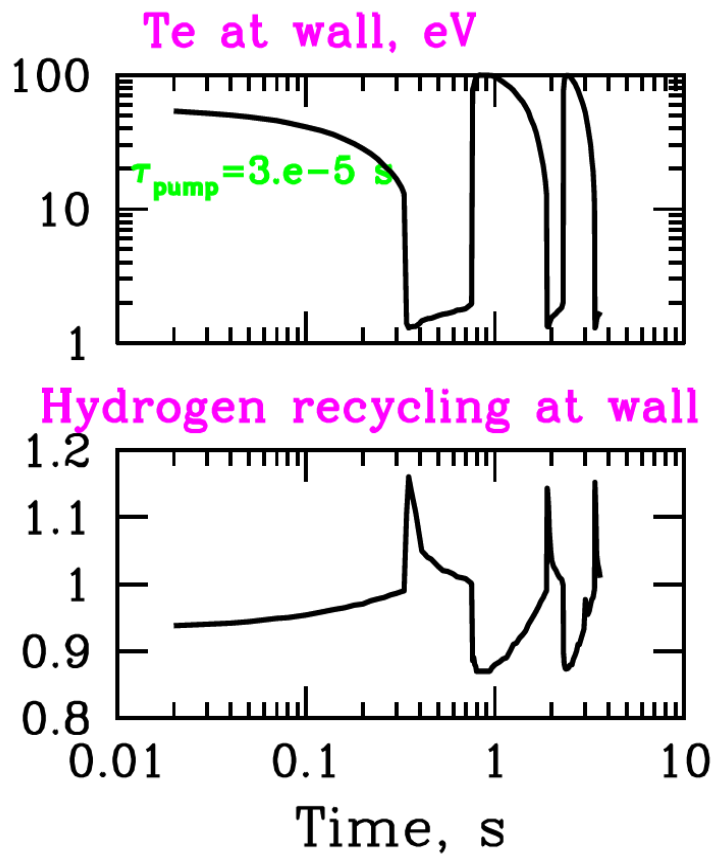
- Transient MARFE-like plasma collapse associated with imbalance of gas source and volumetric + wall pumping rates caused by wall switching to outgassing







- Edge plasma in contact with saturated wall can exhibit self-sustained oscillations



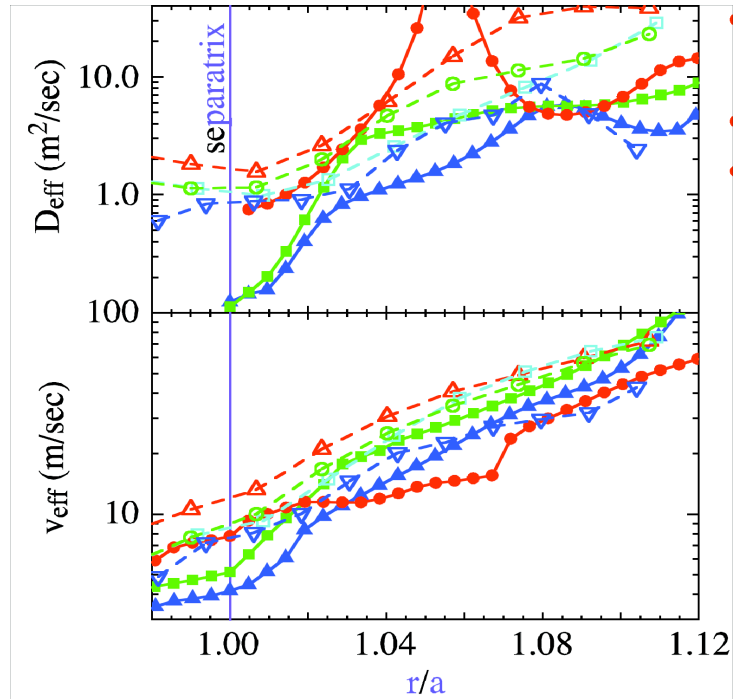
Fusion Energy Program

Related motivation: analysis of H_alpha signals indicate strong fluctuations/transport in far SOL

- DIII-D and Alcator C-Mod H_alpha analysis show large increases in far SOL transport →
- Langmuir probes and gas-puff imaging also see substantial SOL fluctuations/transport (Boedo, Rudakov, Zweben)
- "Blob" propagation model (Krasheninnikov et al.) may explain fast outward motion

We seek a predictive model of turbulence generation and transport

From B. Lipschultz, D. Whyte



DIII-D	$\bar{n}_e/n_{Greenwald}$
▽	0.26
⊟	0.38
⊖	0.45
△	0.58

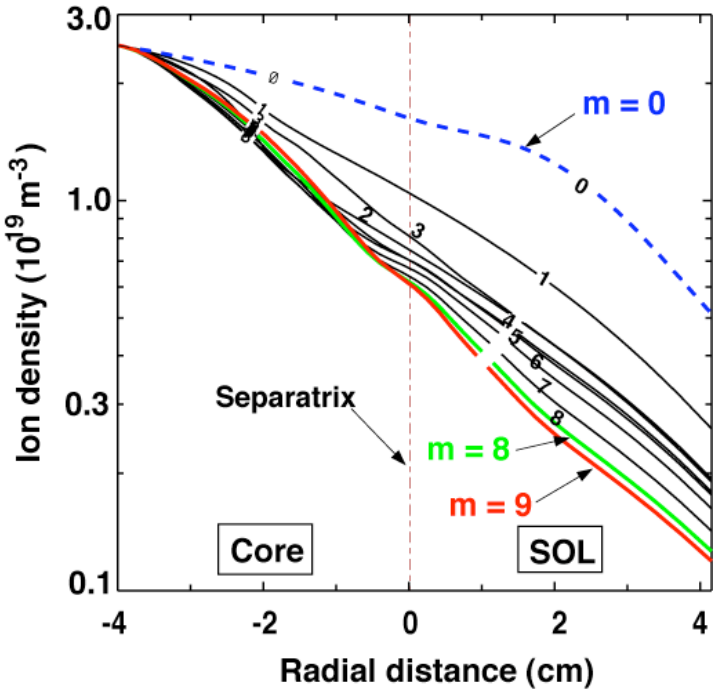
C-Mod	$\bar{n}_e/n_{Greenwald}$
▲	0.16
■	0.23
●	0.36

Fusion Energy Program

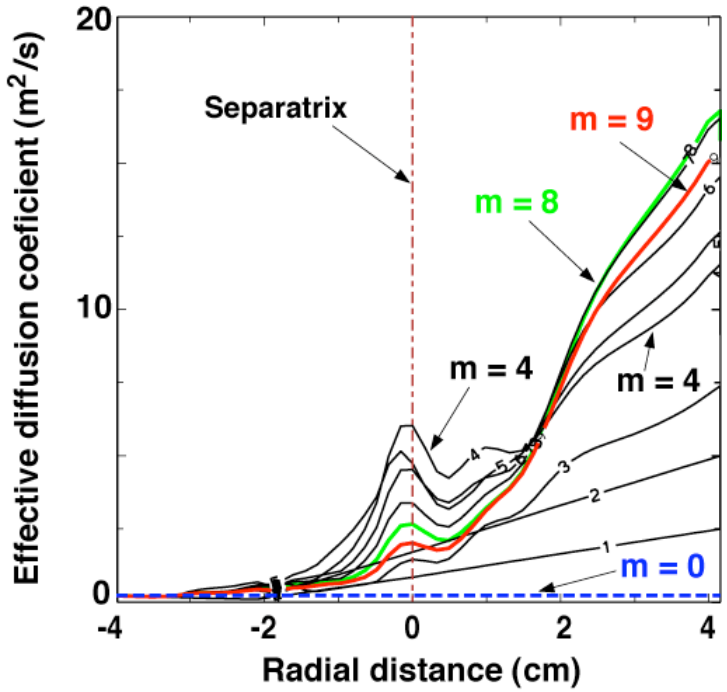
Result of 9 iterations shows an approach to equilibrium with strong outer-SOL transport

- Iterations are performed from m=0 (initial profile) to m=9
- Density profile converges more rapidly that turbulent fluxes

a) Midplane density profile evolution



b) Midplane diffusion coeff. evolution



Fusion Energy Program

WallPSI in more detail: numerous collisional and thermally activated reactions included

- Coupled transport equations of diffusion-advection-reaction type for considered hydrogen species
  - Bulk diffusion coefficient depends on concentration (owing to gradient of chemical potential) and on profile incident ion/neutral flux
  - Non-diffusive transport of mobile species via outward convection caused by nano-void production in implantation region and via inward convection caused by internal pores
  - Reflection coefficients, sputtering yields, hydrogen implantation profile, profile of recoils, profile of penetrating flux are pre-computed with TRYDIN, averaged over incident particle distribution, fitted and tabulated
- Key features currently under development
  - Distinguish dynamic and stationary traps for hydrogen and solve equations for production and dynamics of “broken-bond” traps and related hydrogen trapping
  - Dynamic plasma facing surface interface to model net erosion/deposition (planned)

Fusion Energy Program