Investigation of plasma turbulence in tokamak divertor and its implications for plasma-material interactions

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SOLT3D is a physics model implemented in BOUT++ for turbulence and transport in tokamak SOL and divertor regions

Approximations currently used in the SOLT3D model:

- Electrostatic - not including magnetic perturbations
  - SOL and divertor plasma have very low plasma beta (except ELMs)
  - Radial gradients are not steep (except H-mode pedestal)

- Rectified edge plasma geometry – i.e., toroidal slab w/ branch-cuts
  - Simplifies treatment of metric coefficients etc.
  - Still, captures branch-cut topology essential for edge plasma
  - Sufficient for most issues related to SOL/divertor turbulence and transport
  - Makes easy connection with analytic theory

SOLT3D physics model includes six dynamic fields: N_i, ϖ, T_e, T_i, $V_{||i}$, N_n

Dynamic equations

$$\partial_t N_i = - V_E \cdot \nabla N_i - V_{||i} \cdot \nabla N_i - N_i \nabla \cdot V_{||i} + \nu_{iz} N_i$$

$$\partial_t \varpi = -V_E \cdot \nabla \varpi - V_{||i} \cdot \nabla \varpi + 2\omega_{ci} b_0 \times \kappa \cdot \nabla P + eNi \frac{4\pi V_A^2}{c^2} \nabla_{||} j_{||} - \nu_{cx} \varpi$$

$$\partial_t T_e = - V_E \cdot \nabla T_e + V_{||i} \cdot \nabla T_e + (2/3)\nabla_{||} (\kappa_{||e} \nabla_{||} T_e)/N_i$$

$$\partial_t T_i = - V_E \cdot \nabla T_i + V_{||i} \cdot \nabla T_i + (2/3)\nabla_{||} (\kappa_{||i} \nabla_{||} T_i)/N_i$$

$$\partial_t V_{||i} = - V_E \cdot \nabla V_{||i} - V_{||i} \cdot \nabla V_{||i} - \nabla_{||} P/(M_i N_i)$$

$$\partial_t N_n = D_n \nabla^2 N_n - R_{iz} N_i N_n$$

Algebraic relations

$$j_{||} = \frac{eN_i}{0.51\nu_{ei}} \left(-\frac{e}{m_e} \partial_{||} \phi + \frac{T_e}{N_i m_e} \partial_{||} N_i + \frac{1.71}{m_e} \partial_{||} T_e \right)$$

$$\varpi = eN_i \nabla_\perp^2 \phi + \nabla_\perp^2 Pi$$

$$P = T_e N_i + T_i N_i$$

Poloidal BC: sheath, or zero || gradients for fluctuating quantities

Standard neutral gas physics is implemented in SOLT3D

Reaction rates

- Ionization $R_{iz} = <\sigma v>_{iz} = 10^{-5} \frac{(T_e/E^Z_\infty)^{1/2}}{(E^Z_\infty)^{3/2}(6.0 + T_e/E^Z_\infty)} \exp\left(-\frac{E^Z_\infty}{T_e}\right)$ (NRL formulary)
- Charge-exchange rate $R_{cx} = <\sigma v>_{cx}$; constant cross-section $\sigma_{cx} = 7\text{x}10^{-19}\ \text{m}^2$

Neutral momentum equation reduced to neutral diffusion equation

$$\frac{\partial}{\partial t}(mnV_{\|}) + \nabla\cdot(mn\,V\,V_{\|} - \eta\nabla V_{\|}) =$$
$$= -\nabla P_N - m\,n_N n_i K_{cx}(V-V_i) - m\,S_r V_{\|i} + m\,S_i V_{\|}$$

=>

$$\nabla P_N + m\,n_N n_i\ K_{cx}(V-V_i) = 0$$

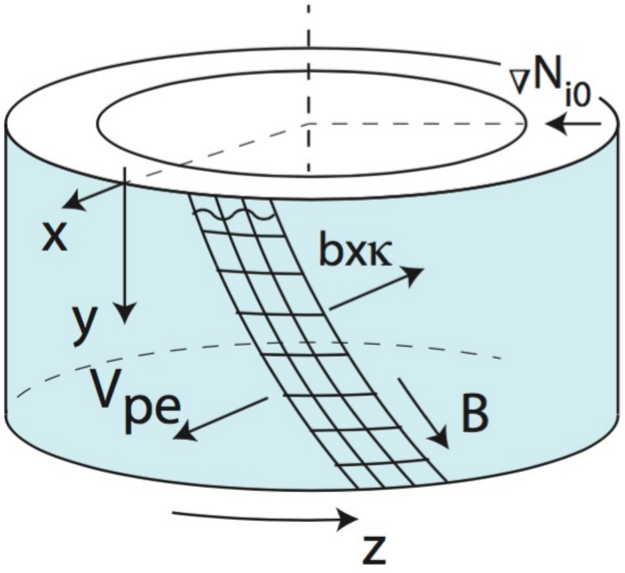
$\Gamma_N = -D\ \text{grad}(n_N)$

$D_n = \lambda_{cx} V_{ti}$

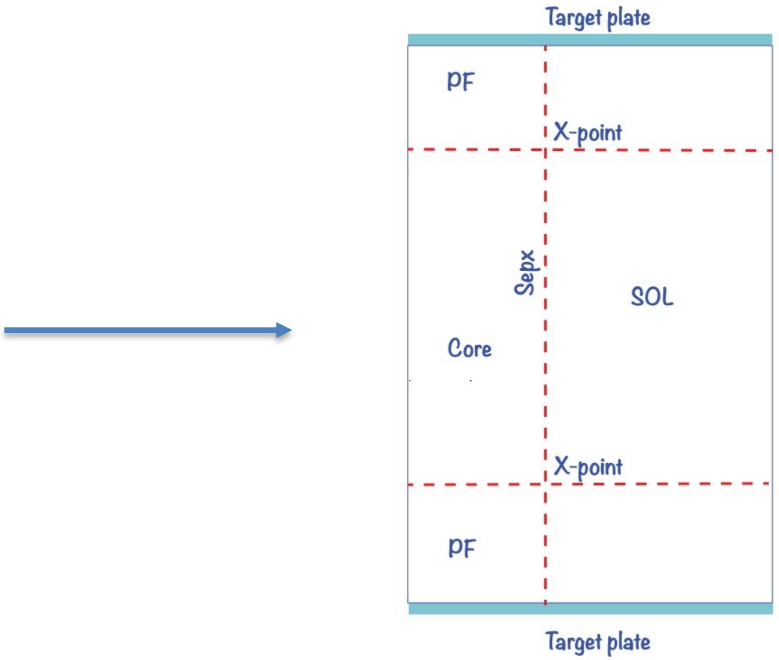
$$\partial_t N_n = D_n \nabla^2 N_n - R_{iz} N_i N_n$$

SOLT3D treatment of the geometry: rectified edge model with branch-cuts

- Toroidal slab



- Rectified edge model w/ branch-cuts



- Toroidal B field ~ 1/R
- Poloidal B field taken as $B_{pol}(R)$, no singularity at X-points
- Rectified edge plasma setup simplifies problems with Reynolds stress E_r

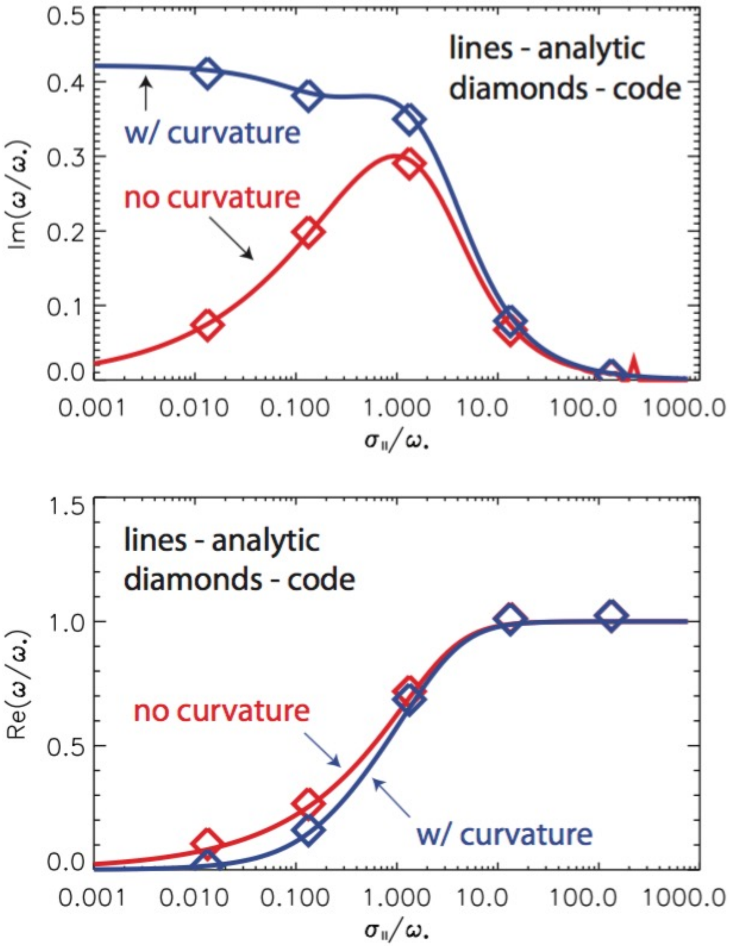
SOLT3D model supports the bulk of physics essential for plasma instabilities, turbulence, and transport in SOL and divertor

- Linear waves and instabilities
  - Resistive-drift, Resistive-ballooning, Sheath-driven instability, Ion acoustic mode
- Nonlinear phenomena
  - Blobs, Turbulence
- Atomic physics
  - Neutral collisional transport, Plasma-neutral interactions

- Extensive verification has been carried out, with fully consistent results
  - Linear tests - Drift-resistive ballooning mode (DRBM), Conducting wall mode (CWM) instability, Acoustic wave, Neutral gas diffusion
  - Nonlinear tests - Plasma blobs, Parallel heat conduction w/ sheath BC, Turbulence in LAPD

SOLT3D results for Drift-Resistive-Ballooning Mode instability match analytic growth rates

Drift-Resistive-Ballooning Instability in SOLT3D



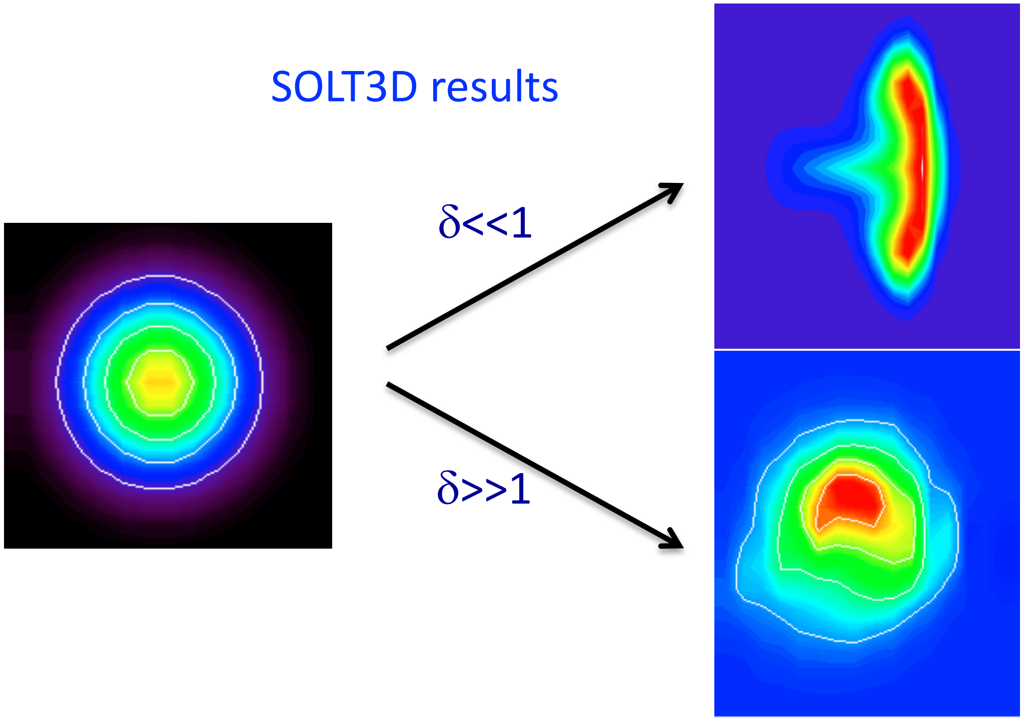
- DRBM is the main plasma instability for SOL and divertor
- DRBM model can include analytically corrections due to
  - Neutrals
  - FLR
  - Parallel heat conduction
- Those corrections have been also verified in the code

SOLT3D results for plasma blobs match previous simulations

Normalized blob size is the figure of merit

$$\delta = \frac{\delta_b}{\delta_*}$$

$$\delta_* = \rho_s \left(\frac{L_{\|}^2}{\rho_s R} \right)^{1/5}$$



SOLT3D results

δ<<1

δ>>1

- For small blobs, δ<<1 KH mushroom breakup,
- For large blobs, δ>>1 interchange breakup
- Consistent with previous published work[1]

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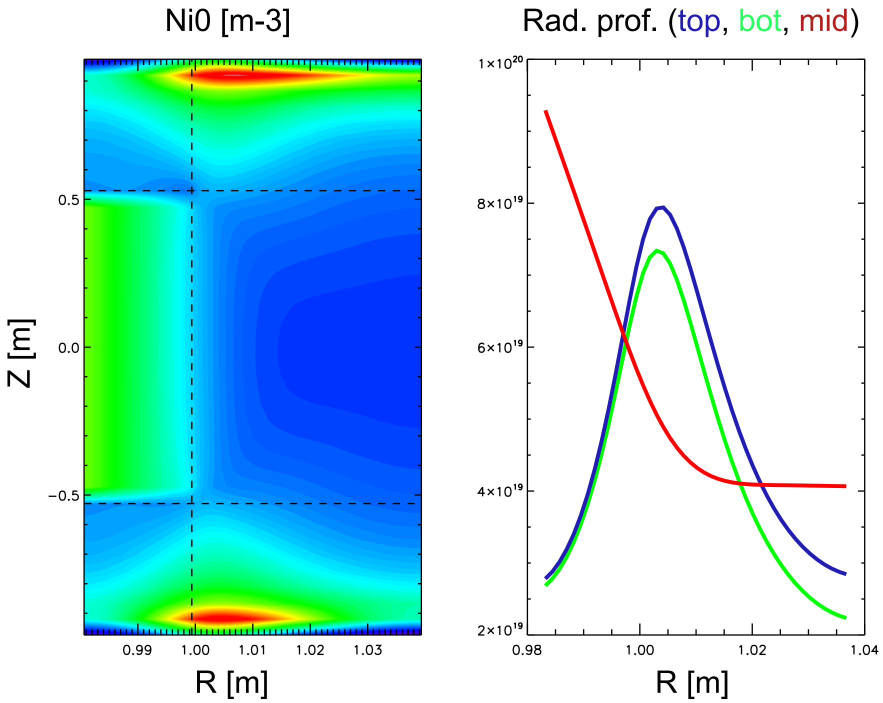
[1] Krasheninnikov, Myra et al., J. Plas. Phys. (2008), vol. 74, part 5, p. 679

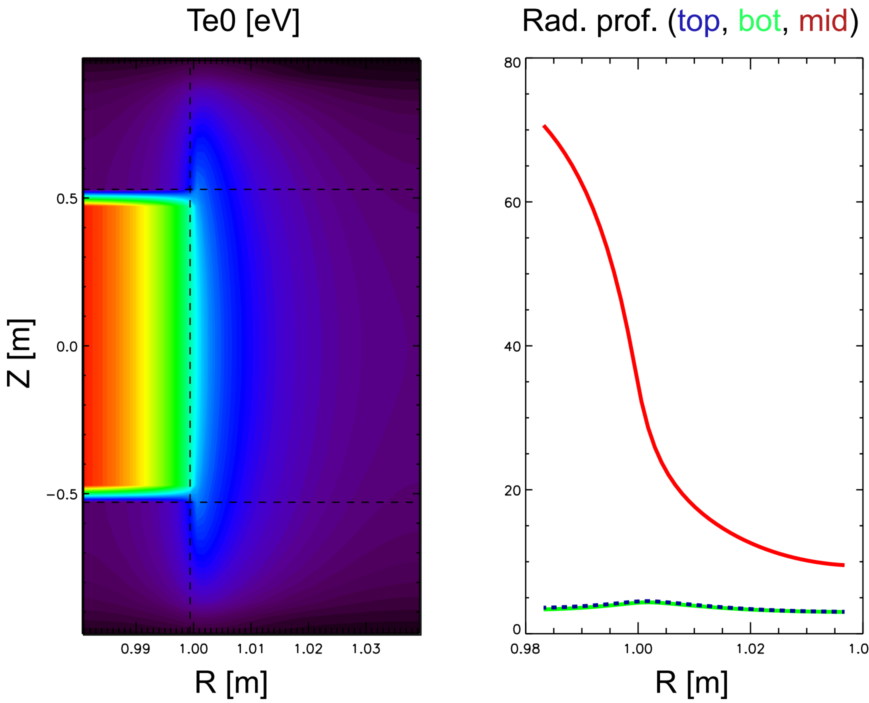
SOLT3D application to L-mode-like edge plasma in medium size tokamak

- Toroidally symmetric edge transport code UEDGE provides background plasma state
- Not evolving toroidally-average plasma profiles of N_i, $V_{||i}$, $T_{e,i}$ in these simulations
- In the simulation model dropping (for now) a few terms that are presumed small

- Axisymmetric N_{i0} from UEDGE



- Axisymmetric T_{e0} from UEDGE

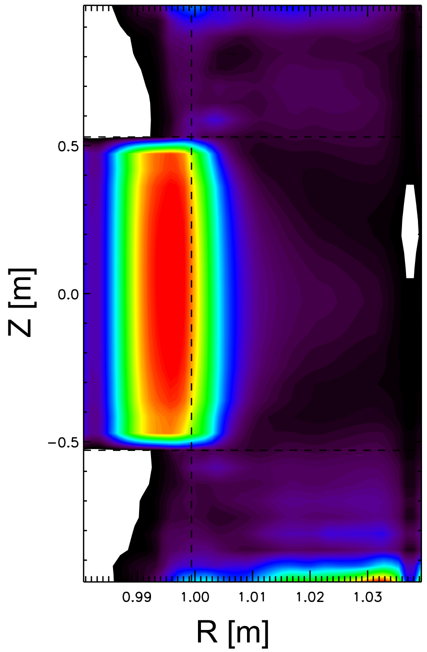


SOLT3D simulations show large fluctuations of plasma parameters at the midplane and at the plates

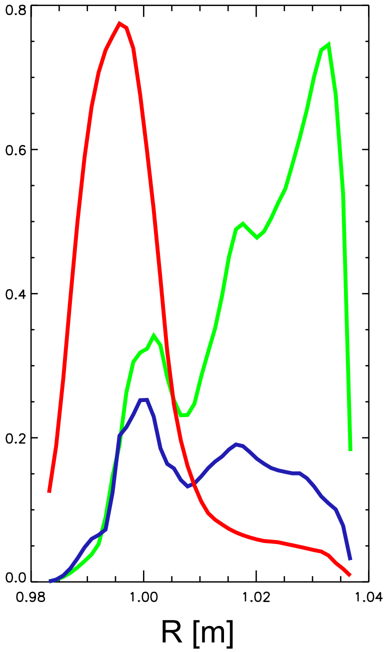
- Fluctuations growth comes to saturation due to the Reynolds stress generated zonal flows and other nonlinearities in the equations

- N_i fluctuations 50-100%
- T_e fluctuations 50-100%

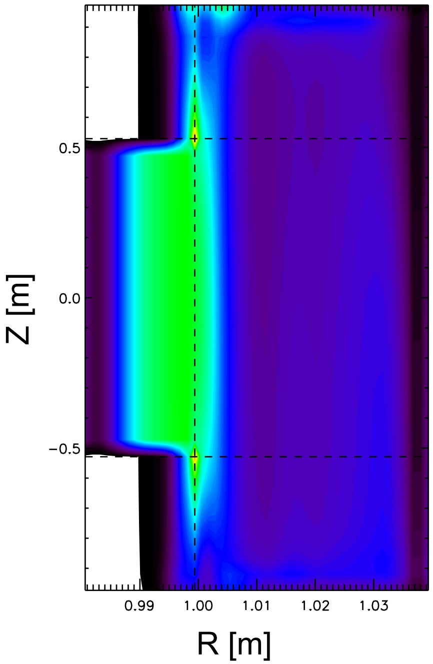
Time-average RMS<Ni>/Ni0



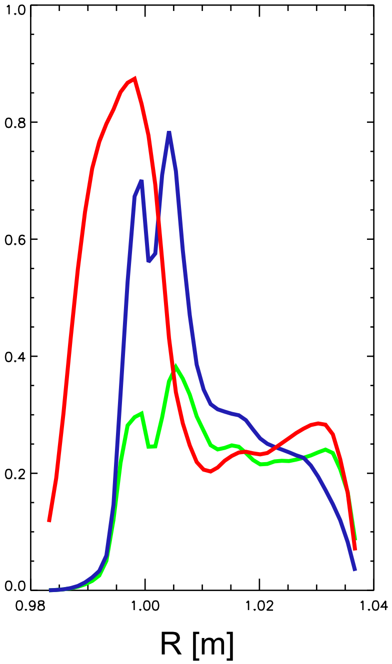
Rad. prof. (top, bot, mid)



Time-average RMS <Te>/Te0



Rad. prof. (top, bot, mid)

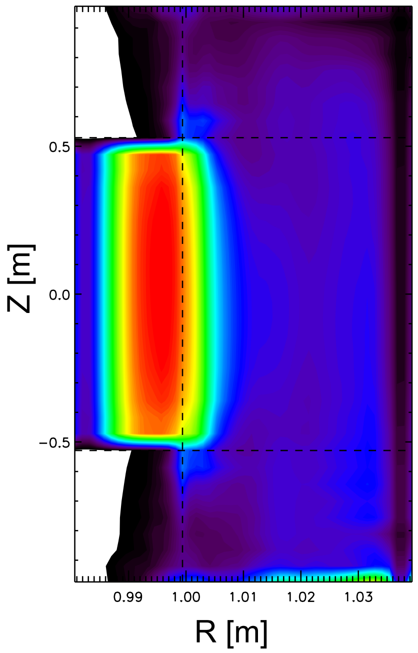


SOLT3D simulations show large fluctuations of plasma fluxes on target plates

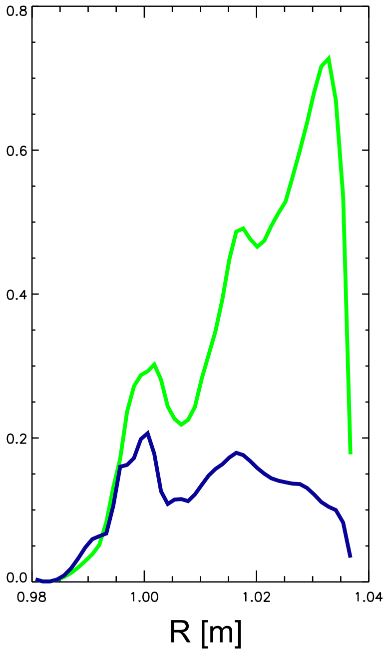
- Plasma fluxes on the plate calculated from fluctuations of N_i and T_e, T_i (Mach=1 condition)

- $\Gamma_{||i}$ fluctuations on plates 50-100%
- $q_{||e}$ fluctuations on plates 50-100%

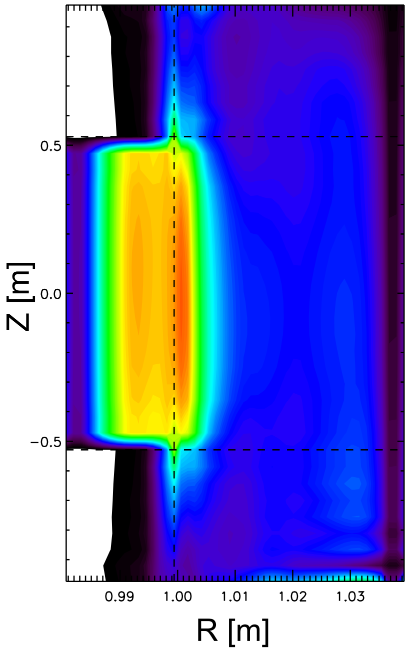
Time-average RMS $<\Gamma_{||i}>/\Gamma_{||i0}$



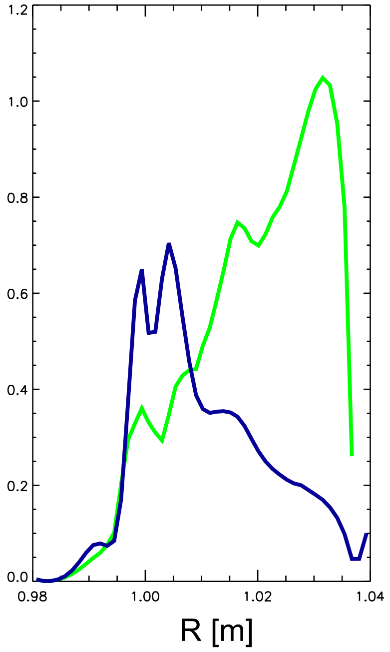
Rad. prof. (top, bot, mid)



Time-average RMS $<q_{||e}>/q_{||e0}$



Rad. prof. (top, bot, mid)



Large SOL/divertor fluctuations in SOLT3D simulations are consistent with experimental data from tokamaks

In the experiment, edge plasma fluctuations are generally measured in tens of %, or more, depending on the location and core plasma parameters

- C-Mod
  - 25-50% fluctuations for n_e, T_e at the midplane [Kube 2019]; 100% fluctuations of n_e, T_e in far SOL, [LaBombard 2001]
- DIII-D
  - 50% fluctuations for n_e, T_e at the midplane [Rudakov 2002]
- NSTX
  - 50-100% fluctuations for n_e, $e\Phi/T_e$ at the midplane [Boedo 2014]
- JET
  - 10-30% fluctuations for J_{sat} at the target plate [Garcıa-Cortes 1996]
- KSTAR
  - 30-40% fluctuations for J_{sat} at the midplane [Garcıa 2017]
- JT-60
  - 20-100% fluctuations for J_{sat} in the divertor [Tanaka 2009]

Kube et al., NME 18, 193–200 (2019); LaBombard et al., Phys. Plasmas, v. 8, n. 5, (2001); Rudakov et al., PPCF 44, p717 (2002); Boedo et al., Phys. Plasmas, 21, 042309 (2014); Garcıa-Cortes et al., Plasma Phys. Control. Fusion 38 (1996) 2051–2062; Garcia et al. Nucl. Mater. Energy 12 (2017) 36–43; Tanaka et al., Nucl. Fusion 49 (2009) 065017

Large fluctuations (tens of %) of plasma parameters and fluxes on PFC may lead to significant quantitative effects for PMI

- Material sputtering rate by ions is strongly sensitive to ion impact energy

- Neglecting plasma fluctuations on PFC may lead to order of magnitude errors in sputtering yield

- Axisymmetric models (UEDGE, SOLPS) miss this effect completely

Sputter yield of W by Ar ions

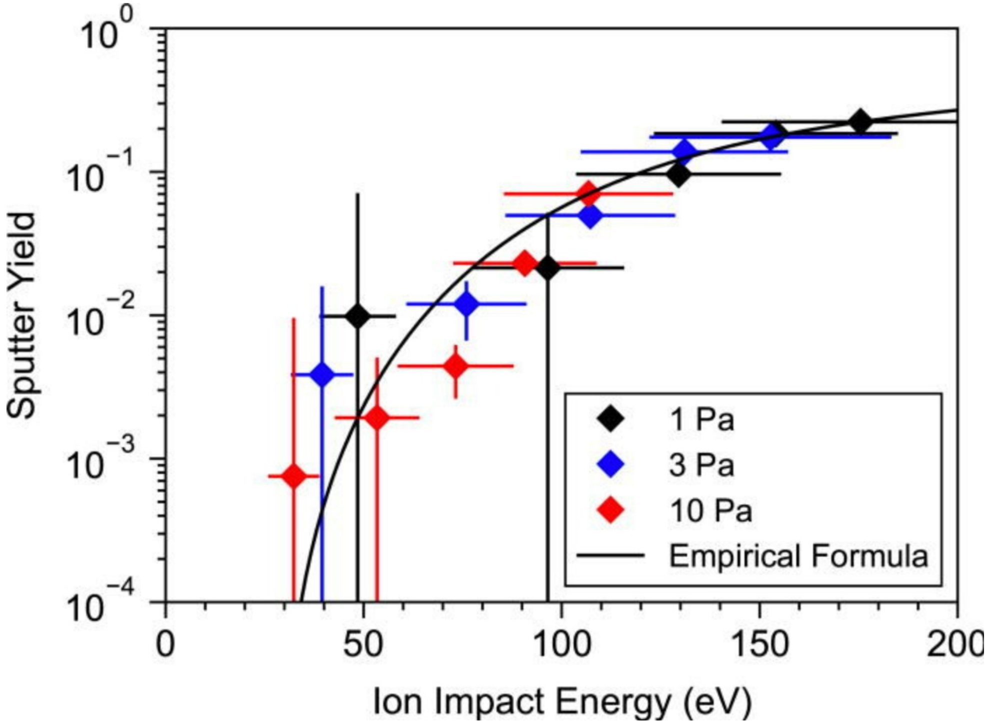


Figure from Sackers et al., Physics of Plasmas 29, 043511 (2022)

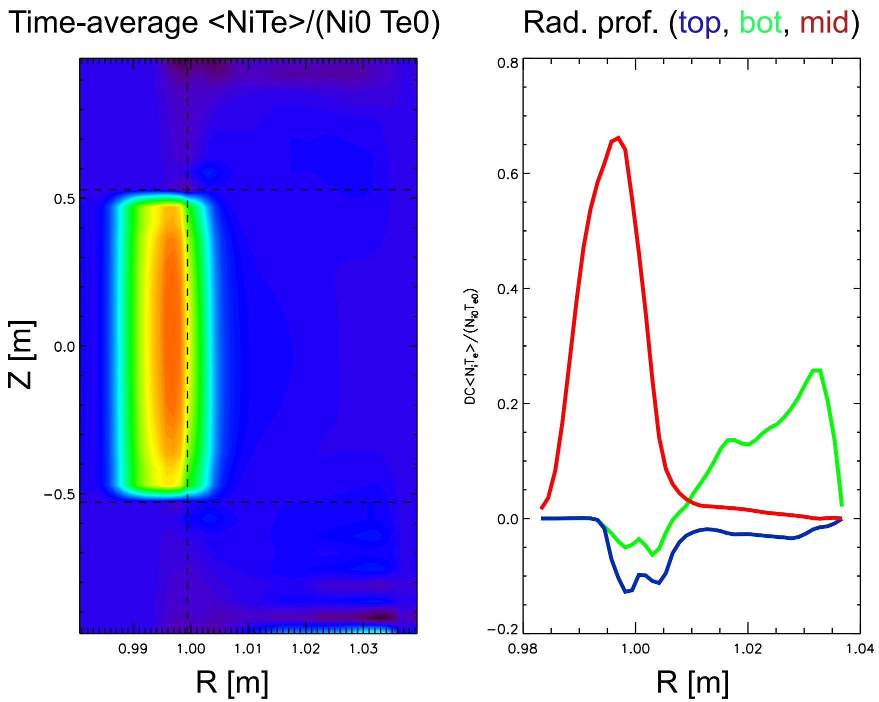
Large SOL/divertor fluctuations lead to intrinsic “noise” in axisymmetric tokamak edge transport modeling

- Edge-transport models (UEDGE, SOLPS etc.) operate w/ toroidally-average quantities
- Presence of turbulent fluctuations introduces errors in all nonlinear relations

- For example, toroidally-average pressure

$$\langle P\rangle = \langle (n_0+n_1)(T_0+T_1)\rangle = n_0T_0 + \langle n_1T_1\rangle$$

Here,
$\langle P\rangle$ = toroidal average *P*
n_0 = axisymmetric *n*
n_1 = non-axisymmetric *n*


Time-average <NiTe>/(Ni0 Te0)
Rad. prof. (top, bot, mid)

Realistic levels of edge plasma turbulent fluctuations (tens of %) give rise to errors on the order of unity for standard toroidally-symmetric edge transport modeling

Implications of fluctuations for standard 2D edge plasma modeling

- Standard 2D edge plasma models (UEDGE, SOLPS, etc.) use the assumptions:
  - Collisional plasma (Braginskii)
  - Axisymmetric plasma and BC
  - Radial transport ad-hoc in form of effective Chi, D

- Accuracy of edge plasma models is intrinsically limited
  - Fluctuations introduce errors in axisymmetric plasma equations

- 2D models match experimental data within a factor ~2 but not better
  - Why?

- The matching error does not improve with collisionality
  - Collisional assumption is not the problem

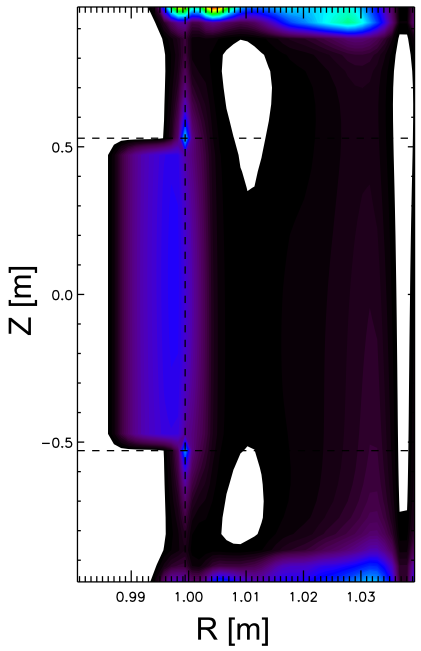
- One needs to be careful making predictions & designs based on 2D edge models
  - Should account for error-bars, at least a factor of ~2

- Coupling of edge turbulence and transport
  - Not enough to provide Chi, D from a turbulence model

Accounting for large SOL/divertor fluctuations may explain some long-standing puzzles in tokamak edge plasma modeling

- Toroidally-average ionization source $\langle S_{iz}\rangle = \langle (n_{i0}+n_{i1})(n_{n0}+n_{n1})R_{iz}(T_{e0}+T_{e1})\rangle$
- Based on SOLT3D simulations, ionization source $\langle S_{iz}\rangle$ ~ 2 $S_{iz,0}$
- Edge plasma fluctuations explains “radiation shortfall”

Time-average (<Siz>/Siz0)-1



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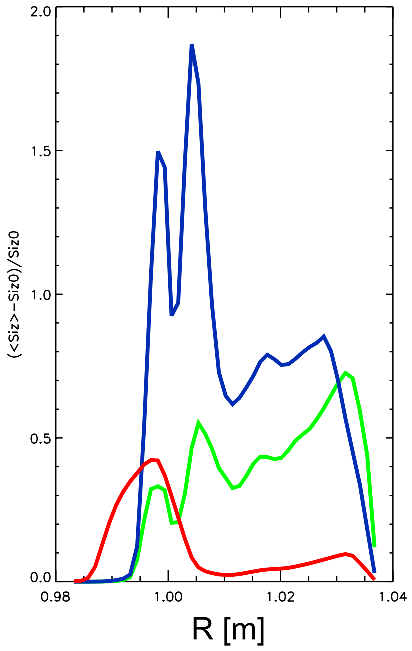

“Radiation shortfall”

- All major 2D edge codes (UEDGE, SOLPS, EDGE2D) underpredict total divertor radiation by a factor of ~2
- In L-mode and H-mode
- In hydrogen plasma and in helium plasma
- Points to some generic feature/deficiency of 2D modeling
- Fluctuations!

M. Groth, APS-DPP 2014
J. Canik, APS-DPP 2016

Discussion & Summary

- SOLT3D is a fluid model for SOL and divertor plasma turbulence, implemented in BOUT++ framework
- Using Braginskii-based fluid equations for six dynamic variables N_i, ϖ, T_e, T_i, $V_{||i}$, N_n using electrostatic approximation, in rectified edge-plasma domain
- SOLT3D reproduces a range of linear plasma instabilities relevant to tokamak edge, comparison with some existing nonlinear results demonstrates consistency
- SOLT3D produces plasma turbulence characteristics that appear generally consistent with experimental measurements in tokamak edge (at least for L-mode),
  - realistic amplitude and spatial dependence of fluctuations
  - realistic plasma fluxes on material surfaces
  - expected Bohm-like effective radial D,χ
- Inferred cross-correlations of fluctuating quantities from SOLT3D simulations imply a significant level of intrinsic "noise" in axisymmetric plasma modeling, introducing errors on the order of unity