Equilibrium & Turbulent far-SOL Transport

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RF-SciDAC : Center for Simulation of Fusion Relevant RF Actuators
http://rfscidac4.org

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Scientific Objectives & Organization of the RF-SciDAC Project

- **Develop an integrated simulation for quantitative prediction of the antenna + sheath + scrape-off-layer + core plasma system which fully utilizes leadership class computing.**
- Validate this predictive capability on appropriately diagnosed experiments including dedicated RF test stands, linear devices, and existing tokamaks.
- Project organized into 4 thrusts:
  - Thrust 1: RF WDM Components & Thrust Common Efforts **(other poster)**
  - Thrust 2: RF + Turbulence **(this poster)**
  - Thrust 3: RF + Equilibrium Transport **(this poster)**
  - Thrust 4: RF + Impurity Generation **(other poster)**
- **Use these tools to inform design of robust, impurity-mitigating RF heating and current drive sources for future fusion devices.**

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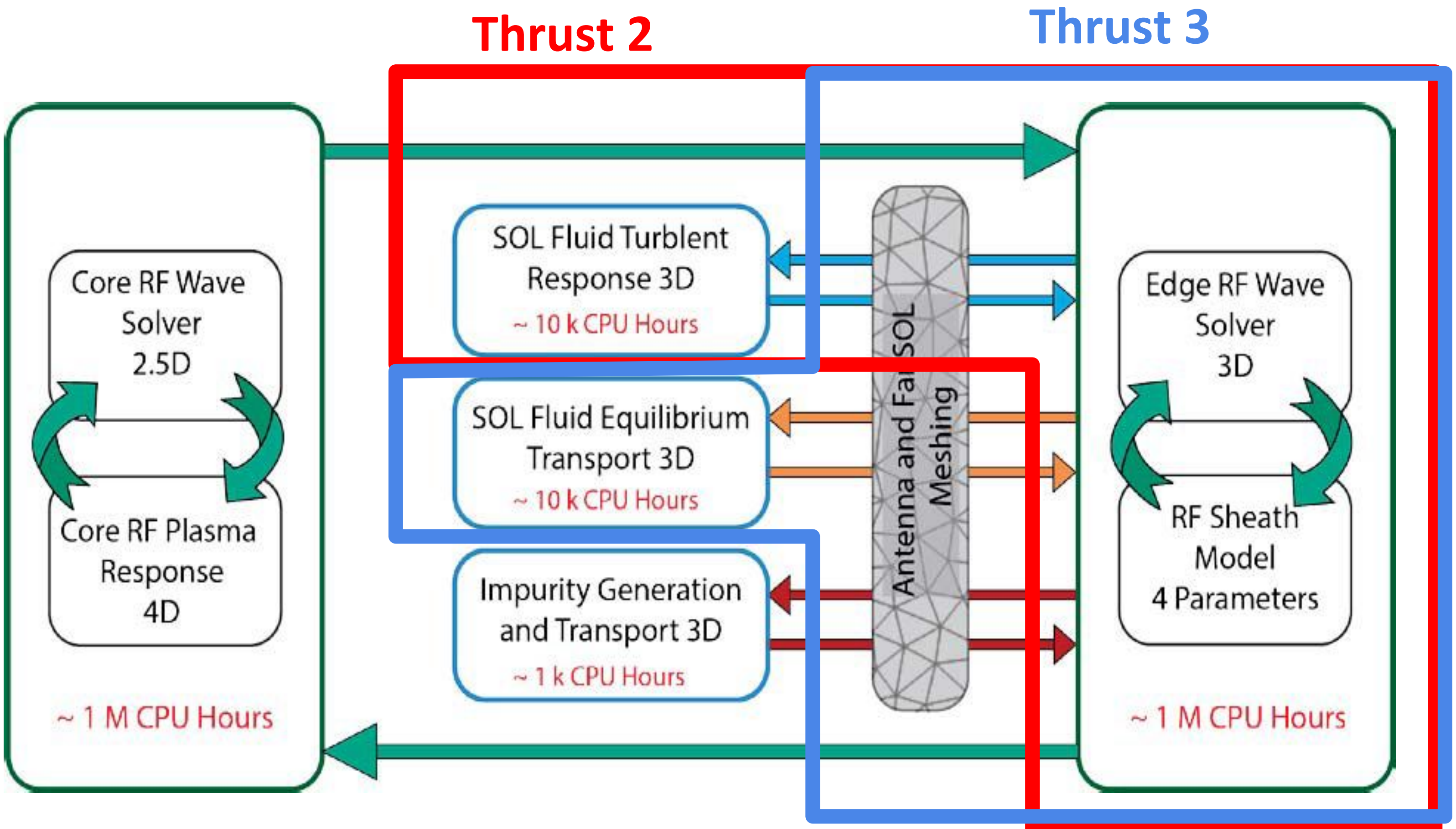
Thrusts 2&3 : Coupling of RF to turbulent and equilibrium timescale transport



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Braginskii miniapp based on MFEM tests new fluid plasma transport solver

- Physics Model
  - Classical parallel transport with cross-field drifts and ad hoc cross-field diffusion terms
  - Two-fluid model for transport of a single ion species and electrons
  - Diffusion model for a single species of neutral atoms

- Computational Model based on MFEM
  - Coupled system of non-linear partial differential equations
  - Fields discretized using Discontinuous Galerkin Finite Elements of arbitrary order
  - Time integration using high-order SDIRK methods
  - Time step selection using Proportional-Integral-Derivative (PID) Controller
  - Adaptive mesh refinement based on weighted error estimates of each field

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Equations solved

- Currently neglecting drifts, recombination, ohmic heating
- Density evolution

$$\frac{\partial n_n}{\partial t} = \boldsymbol{\nabla} \cdot (D_n \boldsymbol{\nabla} n_n) - n_e n_n \langle \sigma v \rangle_{iz} ,$$
$$\frac{\partial n_i}{\partial t} = -\nabla_{||} (n_i v_{||i}) + \nabla_\perp \cdot (D_{i\perp} \nabla_\perp n_i) + n_e n_n \langle \sigma v \rangle_{iz}$$

- Parallel momentum

$$\frac{\partial m_i n_i v_{||i}}{\partial t} = -\nabla_{||} \left(m_i n_i v_{||i}^2 + p_e + p_i - \eta_{i||} \nabla_{||} v_{i||} \right)$$
$$+\nabla_\perp \cdot (m_i v_{||i} D_{i\perp} \nabla_\perp n_i + \eta_\perp \nabla_\perp v_{i||}) + m_i v_{||n} S_{iz}$$

- Electron and ion energy

$$\frac{\partial}{\partial t} T_e = -v_{||e} \nabla_{||} T_e - \frac{2}{3} T_e \nabla_{||} v_{||e} + \frac{2}{3} \frac{1}{n_e} \nabla_{||} (n_e \chi_{||e} \nabla_{||} T_e)$$
$$+ \frac{2}{3} \frac{1}{n_e} \nabla_\perp \cdot (n_e \chi_{\perp e} \nabla_\perp T_e) + \frac{2}{3} T_e \nabla_\perp \cdot \left(\frac{D_\perp}{n_e} \nabla_\perp n_e \right)$$
$$+ \frac{D_\perp}{n_e} \nabla_\perp n_e \cdot \nabla_\perp T_e - \frac{2 Z_i}{\tau_e} \frac{m_e}{m_i} (T_e - T_i) - \frac{S_{iz}}{n_e} \left(T_e + \frac{2}{3} \phi_{iz} \right)$$
$$\frac{\partial}{\partial t} T_i = -v_{||i} \nabla_{||} T_i - \frac{2}{3} T_i \nabla_{||} v_{||i} + \frac{2}{3} \frac{1}{n_i} \nabla_{||} (n_i \chi_{||i} \nabla_{||} T_i)$$
$$+ \frac{2}{3} \frac{1}{n_i} \nabla_\perp \cdot (n_i \chi_{\perp i} \nabla_\perp T_i) + \frac{2}{3} T_i \nabla_\perp \cdot \left(\frac{D_\perp}{n_i} \nabla_\perp n_i \right)$$
$$+ \frac{D_\perp}{n_i} \nabla_\perp n_i \cdot \nabla_\perp T_i + \frac{2 Z_i}{\tau_e} \frac{m_e}{m_i} (T_e - T_i) + \frac{S_{iz}}{n_i} T_i ,$$

- Potential equation, derived from vorticity, will be solved in future version

Testing high order basis functions for anisotropy

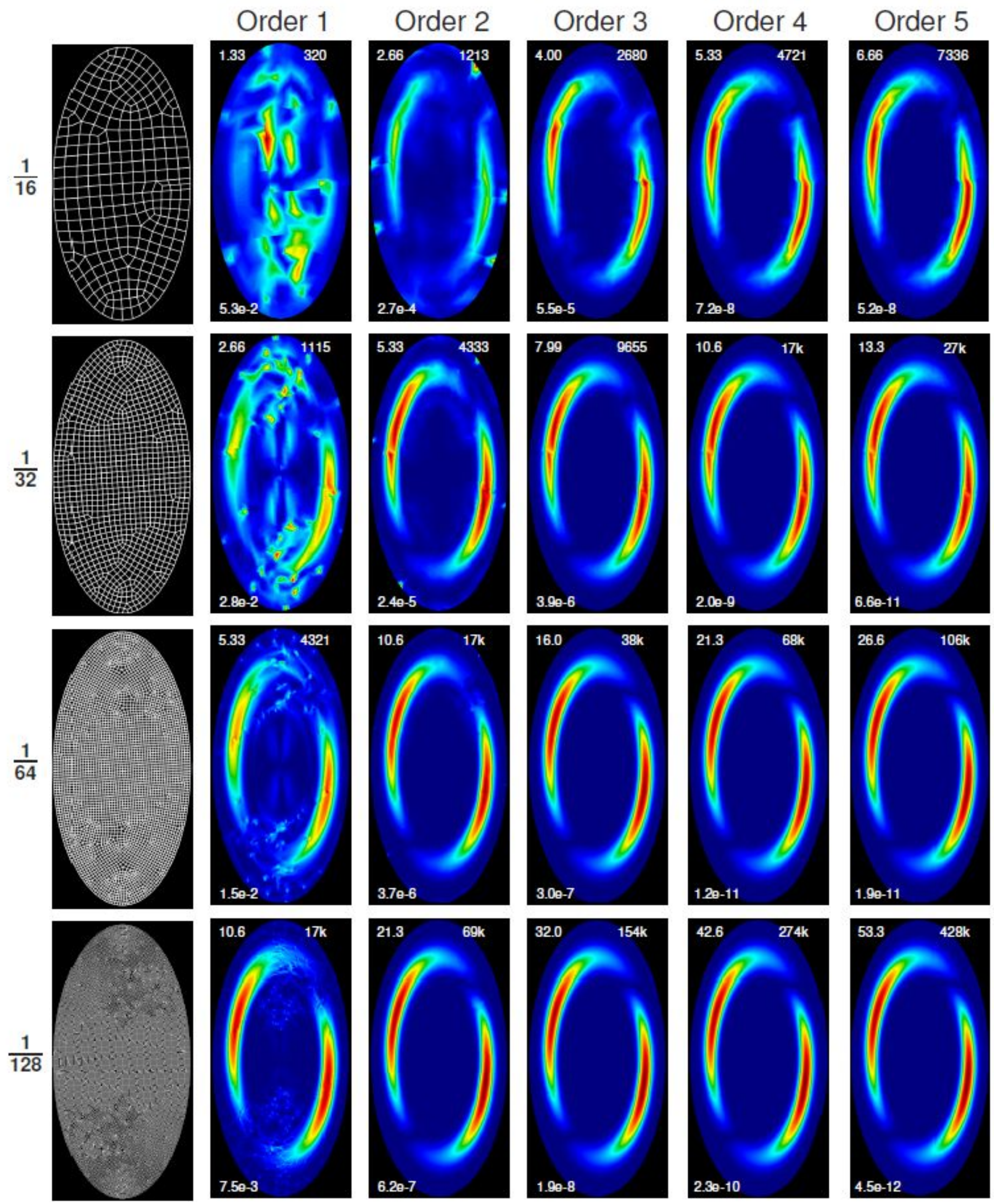
- Plasma transport is highly anisotropic
- High order basis functions tested in using MFEM

$$c_p \frac{\partial T}{\partial t} - \nabla \cdot [\chi \nabla T] = Q$$

Where χ is an anisotropic tensor given by: $\chi = \chi_\perp \left(I - \hat{n}\hat{n}^T \right) + \chi_\| \hat{n}\hat{n}^T$ with $\chi_\| \gg \chi_\perp$

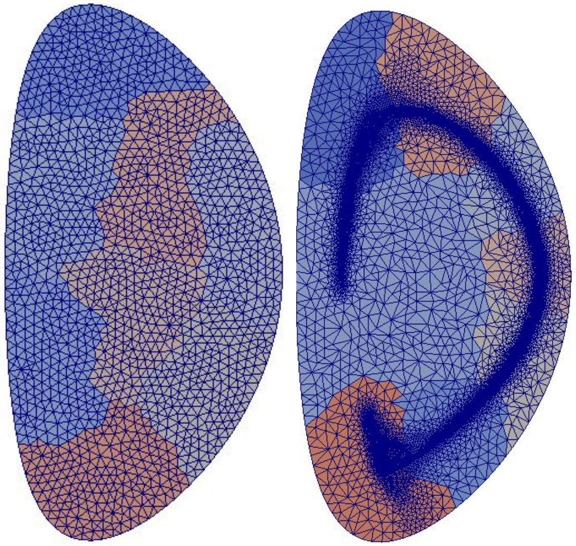
- $\chi_\| / \chi_\perp = 10^3, \ldots, 10^9$
- Mesh densities $h = \frac{1}{16}, \ldots, \frac{1}{128}$
- Basis function orders $p = 1, \ldots, 5$
- Need > 16 interpolation points across features of interest

Parallel Diffusion Results for $\chi_\| / \chi_\perp = 10^9$

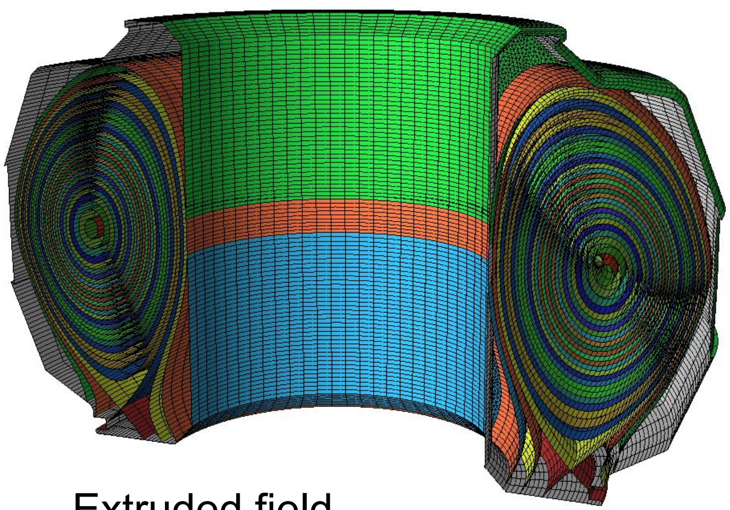


Geometry and Unstructured Meshing

- Geometry
  - Tokamak geometries: ITER, DIII-D, Alcator C-MOD, NSTX, KSTAR, etc.
  - Combined physical and physics entities in model to be meshed to support field aligned meshing and coupling
  - EFIT physics geometry
- Mesh generation (with Simmetrix)
  - Mesh controls to support analysis codes
  - Higher order curved mesh adaptation
  - General and field aligned meshes
  - 2-D and 3-D extruded meshes
  - Support for conforming mesh adaptation



Unstructured initial and adapted mesh



Extruded field aligned mesh

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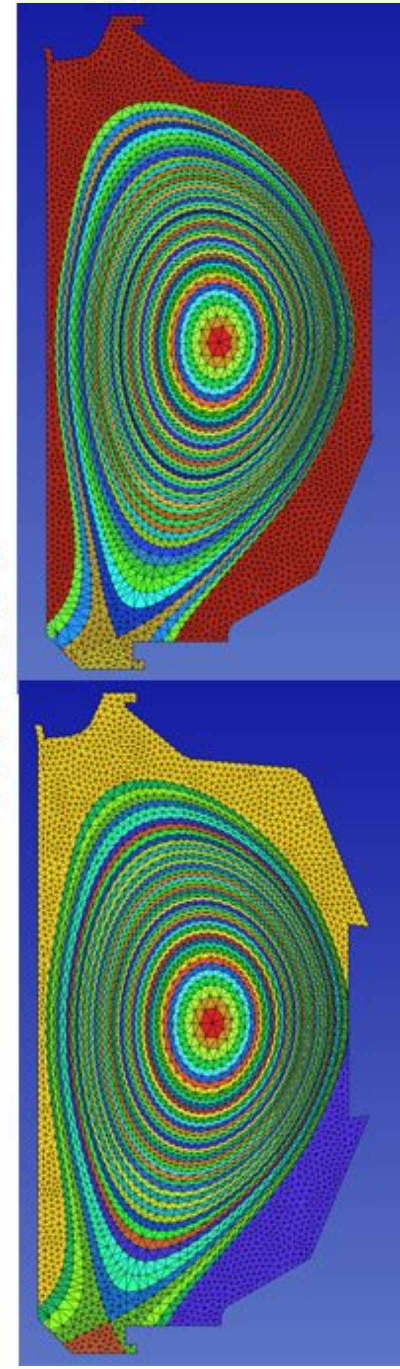
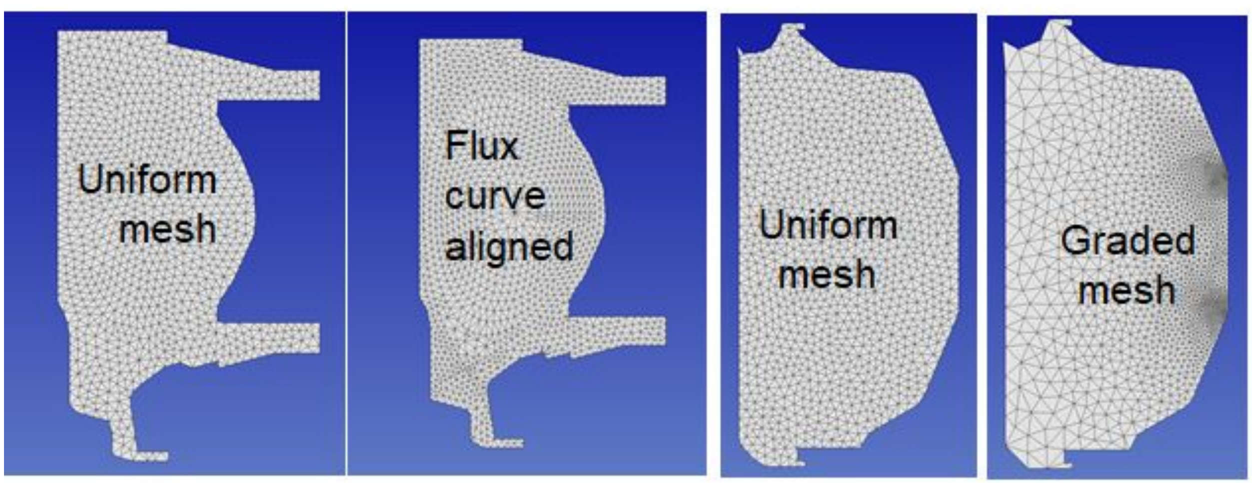
Geometry and Unstructured Meshing

- On going meshing activities
  - Performing initial tests on realistic geometries
  - Comparing alternative mesh configurations
    - Unstructured meshes with general mesh gradations
    - Unstructured meshes with alignment to flux surfaces
    - Meshing modified geometries



Flux surface aligned mesh
Top – original geometry
Bottom – modified Geometry



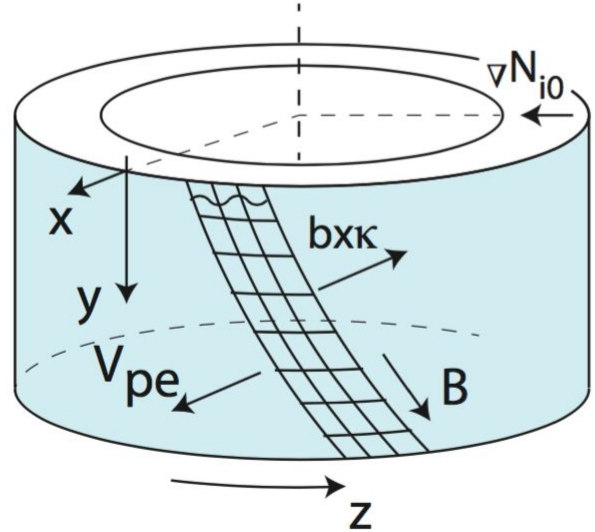
SOLT3D is a 3D BOUT++-based generalization of the highly successful 2D SOLT1 code

Dynamic equations

$$\frac{\partial N_i}{\partial t} = -V_E \bullet \nabla N_{i0} - V_E \bullet \nabla N_i$$

$$\frac{\partial \varpi}{\partial t} = -\left(V_{E0} + V_E\right) \bullet \nabla \varpi + 2\omega_{ci} b_0 \times \kappa \bullet \nabla P + N_{i0} Z_i e \frac{4\pi V_A^2}{c^2} \nabla_\parallel j_\parallel$$

$$\frac{\partial T_e}{\partial t} = -\left(V_{E0} + V_E\right) \bullet \nabla T_{e0} - V_E \bullet \nabla T_e$$



Algebraic constraints

$$j_\parallel = \frac{N_{i0}}{0.51\nu_{ei}} \left(-\frac{e}{m_e} \partial_\parallel \phi + \frac{T_{e0}}{N_{i0} m_e} \partial_\parallel N_i \right)$$

$$\varpi = N_{i0} \nabla_\perp^2 \phi$$

$$P = T_{e0} N_i$$

Sheath B.C.

$$\frac{j_{\parallel,BC}}{j_{\parallel 0}} = \pm \left(\Lambda_1 \frac{e\phi}{T_{e0}} - \Lambda_1 \frac{T_e}{T_{e0}} \right)$$

$$j_{\parallel 0} = C_{s0} N_{i0} e$$

- Implements the drift-reduced-ballooning fluid equations, including curvature drive, and divertor-plate sheath BC's
- Initially using simplified geometries to facilitate implementation of the key divertor-plasma physics
- Have runs with LAPD and tokamak-divertor parameters
- Will add T_i, $V_{||i}$, N_g equations

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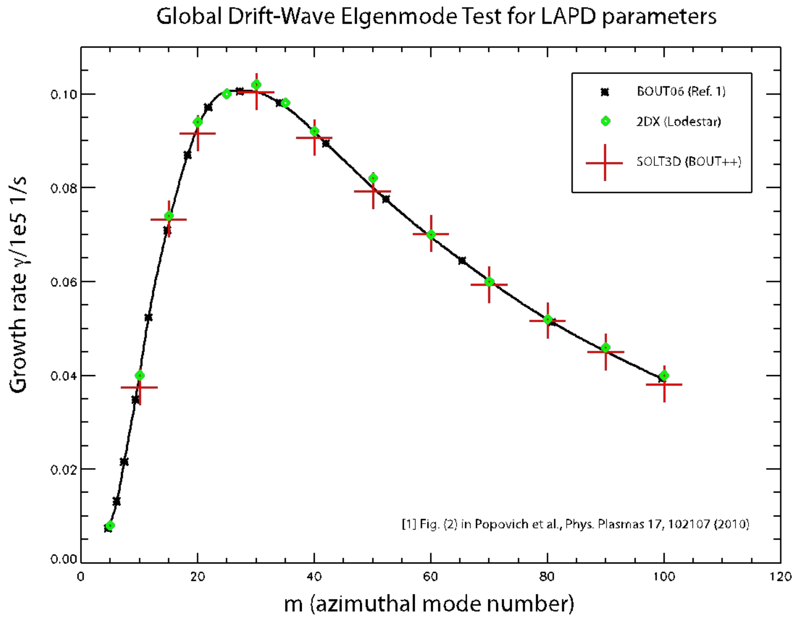
SOLT3D has passed key linear benchmarks

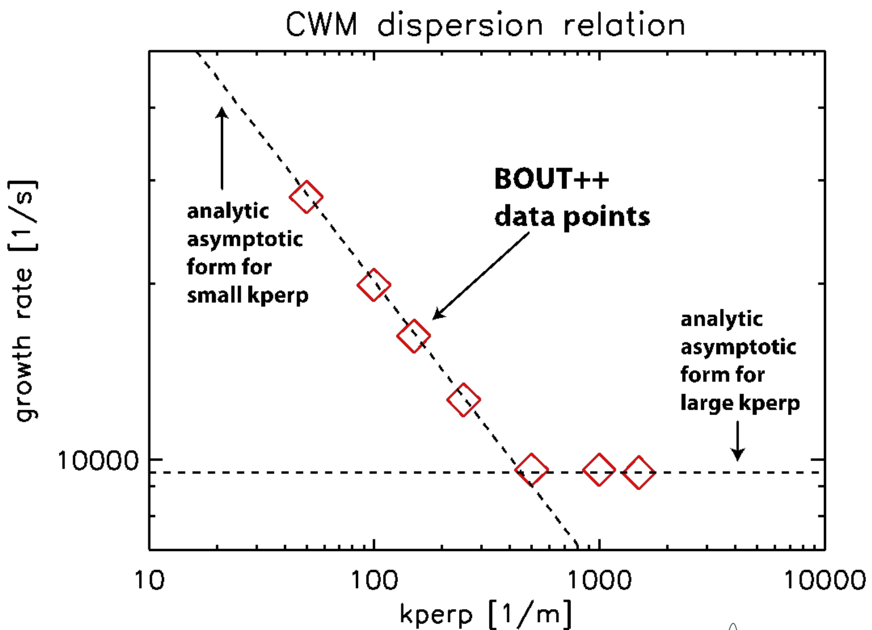
Drift-ballooning benchmarks:

- Local - against analytical theory
- Global - against 2DX[1]

Conducting-wall-mode benchmarks:

- Local against analytical theory





[1]D.A. Baver, J.R. Myra, and M.V. Umansky, Comp. Phys. Comm. **182**, 1610, (2011)

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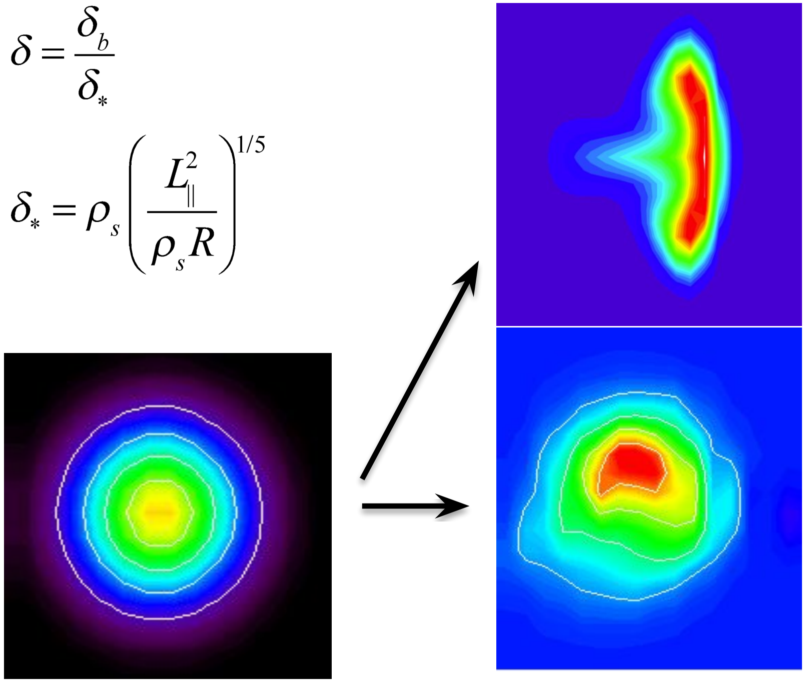
Nonlinear SOLT3D simulations match previous published results

SOLT3D blob simulations agree with previous published results[1]

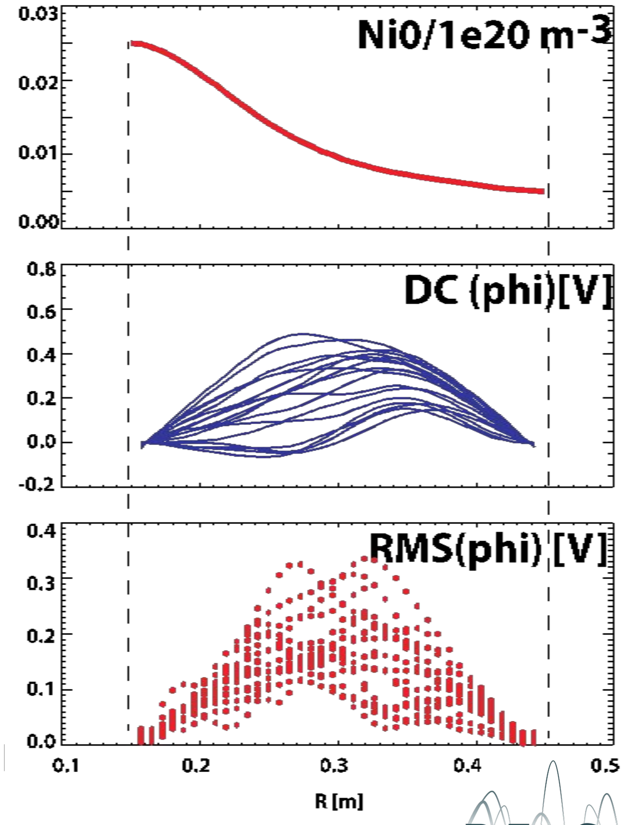
small blobs - δ<<1: KH mushroom breakup
large blobs - δ>>1: interchange breakup

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

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



SOLT3D simulations of drift plasma turbulence for LAPD-like parameters agree with previous published results[2]



[1]Krasheninnikov et al., J. Plas. Phys. **74**, 679 (2008)
[2]Popovich et al. Phys. Plasmas **17**, 10.1063 (2010)

Inclusion of RF effects in the turbulence simulations: Ponderomotive force

- The ponderomotive force is, basically, the lo-pass filter of the following (which will be taken by Vsim)

$$\mathbf{F}_s \equiv \rho_{s1}\mathbf{E}_1 + \mathbf{J}_{s1}\times\mathbf{B}_1 - ({}^{m}/{}_{q})_s \nabla\cdot\left[\frac{\rho_{s0}^2 \mathbf{V}_{s1}\mathbf{V}_{s1}}{\rho_{s0}+\rho_{s1}} \right]$$

- Qualitative understanding from

$$\mathbf{F}_s = -\rho_{s0}\nabla(\psi_p/Ze) + \mathbf{B}\times(\nabla\times\mathbf{M})$$

- First term is gradient of “wave pressure”
  - Second term is … well … extra
- Generates parallel forces, FxB drifts and vorticity sources in low-frequency (BOUT) equations

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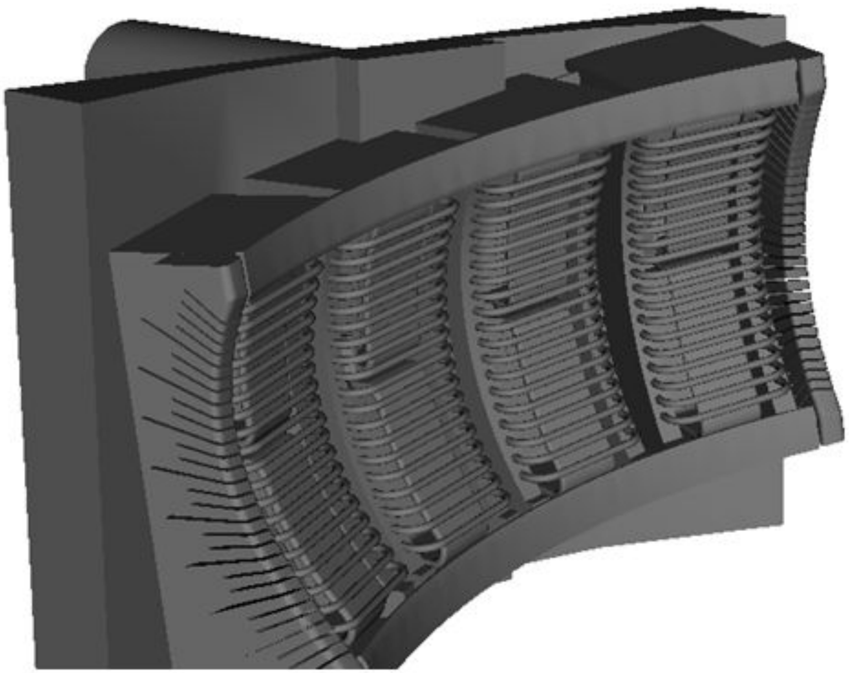
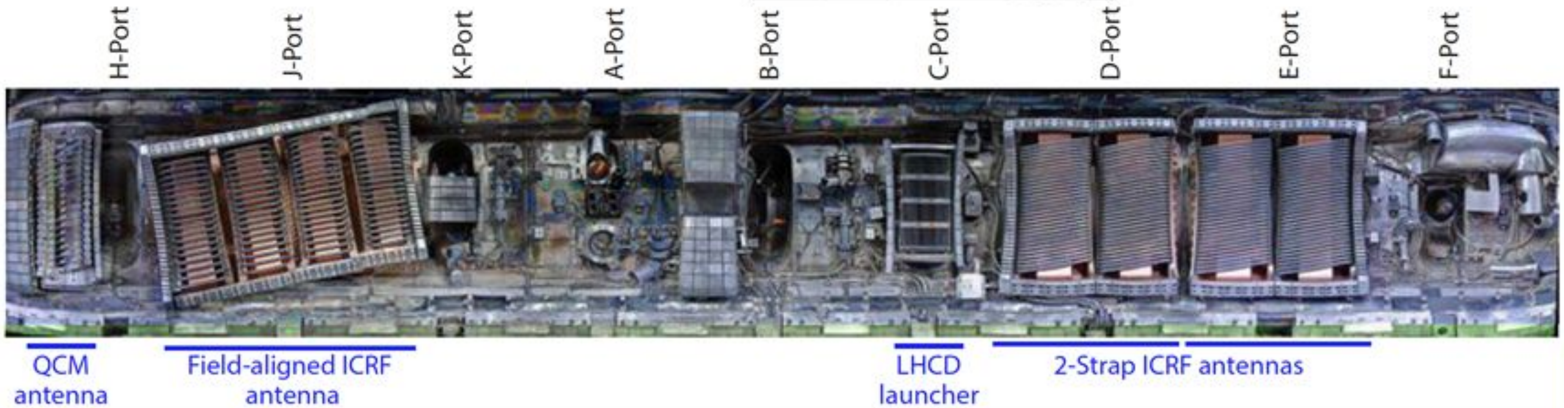
SOL turbulence and transport simulations should include the ponderomotive force

- $|\text{Amplitude}|^2$ steady-state "pressure" from the RF's $|E|^2$, $|B|^2$, and $|JRF|^2$ energy, as it propagates through the steady-state plasma.
- Fast wave, E ~ 5.0×10^4 V/m --> Like 0.1eV
- Slow wave, E ~ 1.5×10^5 V/m --> Like 1eV
- If slow waves are present, will they cause density rarefication in front of antenna, thus perpetuating the low density that favors the slow wave. (Chicken / Egg problem).

What is VSim?

- 3D-FDTD-EM-PIC
  - Cold plasma fluid algorithm, works for ICRH times
  - No PIC particles for this!
  - Good for edge plasma, not good for core absorption
- Import 3D CAD files or generate complex geometry
  - Include the waveguide feeds
  - Includes RF sheath sub-grid model at metal surfaces





Progress has been made on the VSim <--> BOUT++ data transfer and workflow

- BOUT++ -> VSim
  - Density profiles/fields

- At first, data in files, manual runs.
  - VSim likes HDF5, BOUT++ likes NetCDF
  - A Python translation code has been written for BOUT++ --> VSim data transfer

- VSim -> BOUT++
  - Ponderomotive Force
    - First, we are testing SOLT3D with analytical model terms that mimic output expected from Vsim
    - Direct coupling will follow once issues explored with model

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Inclusion of RF effects in the turbulence simulations: RF-sheath boundary conditions in BOUT++ (SOLT3D)

- Want to study effects of boundary conditions resulting from RF launching structures on turbulent solutions e.g., from SOLT3D
- Presently available BOUT++ mesh classes do not allow for impinging structures
- Spatially dependent boundary conditions on an outer flux surface may be adequate
- Use steady solutions of the SOLT3D model implemented in a FEM package (presently COMSOL) to determine boundary conditions on a flux surface, given those at the material surfaces

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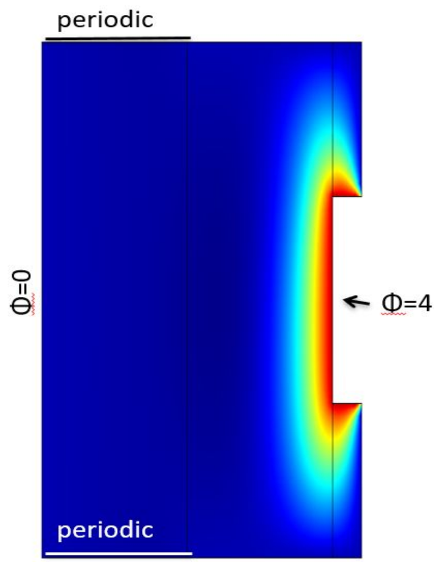
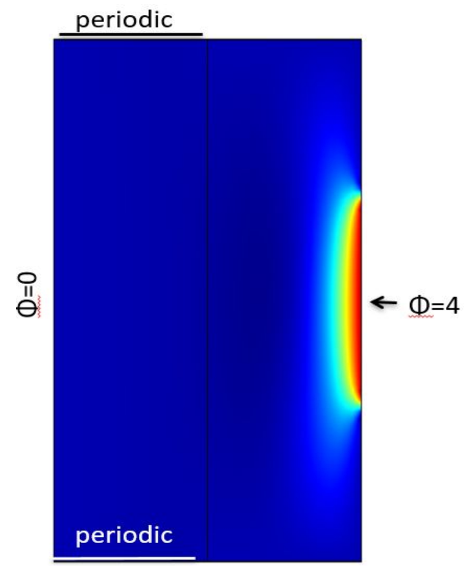
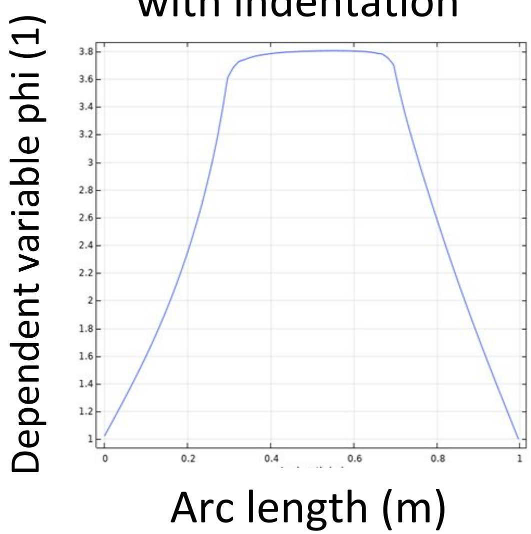
COMSOL solution of DRBM equations w. biased boundaries; w/o & w. indentation - ϕ

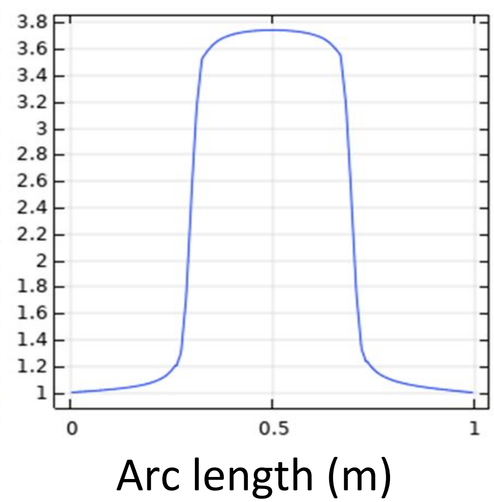




with indentation

without indentation





lineouts

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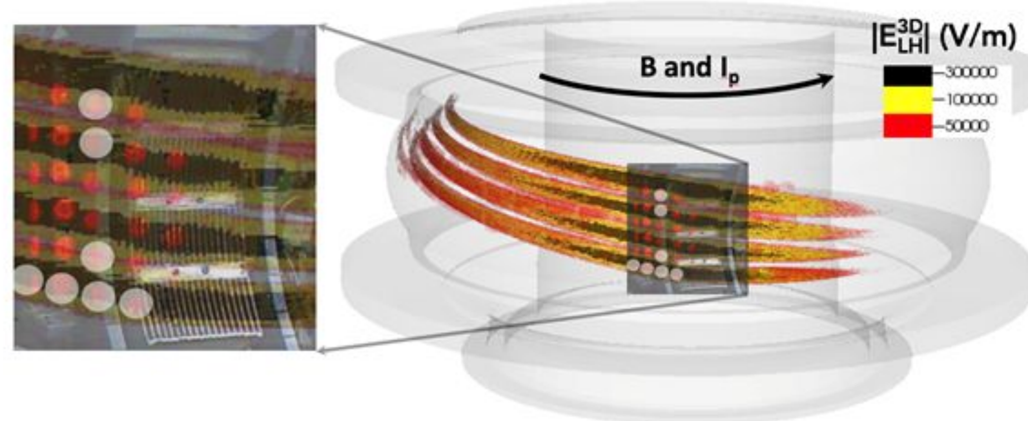
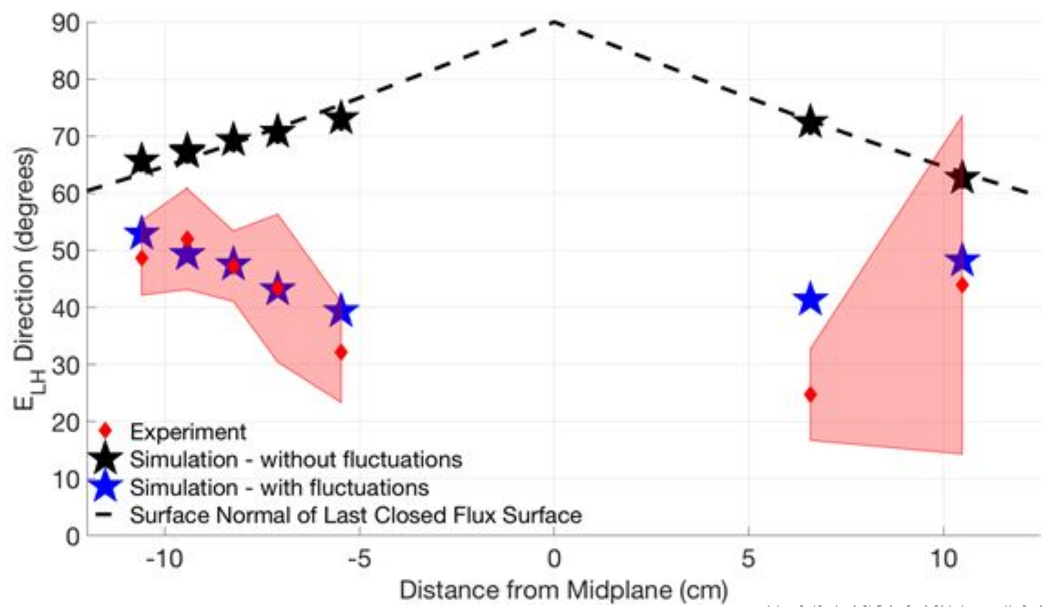
RF simulations originally motivated by experimental measurements of $\bar{E}_{LH}$

- New dynamic Stark effect spectroscopy measurement technique developed to measure magnitude and direction of $\bar{E}_{LH}$ on Alcator C-Mod[1,2]
- Without synthetic fluctuations, measurement and RF simulation agree for magnitude, disagree for direction of $\bar{E}_{LH}$
- With synthetic fluctuations, there could be much better agreement between measurement and RF simulation for direction of $\bar{E}_{LH}$





[1]Martin et. al, IAEA2018, [2]Martin et. al, NF2019

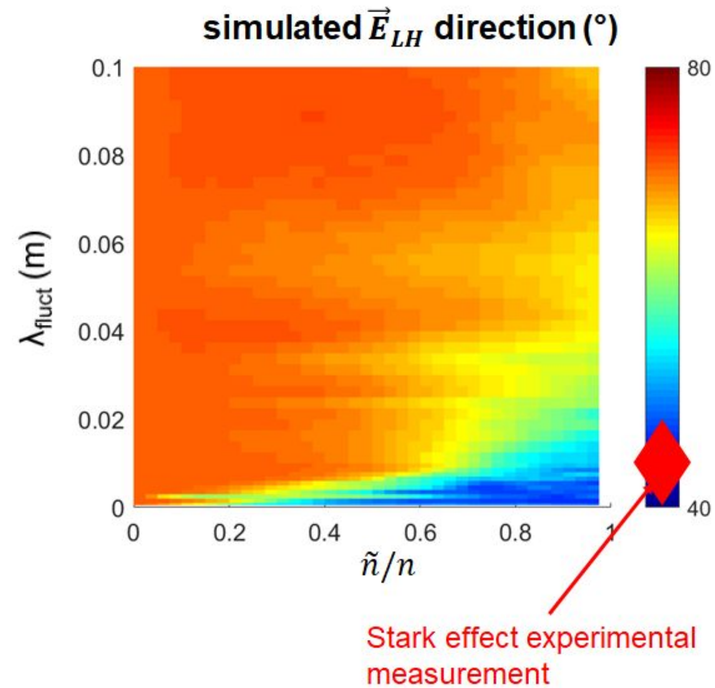
E-field polarization can be significantly modified by different turbulence parameters

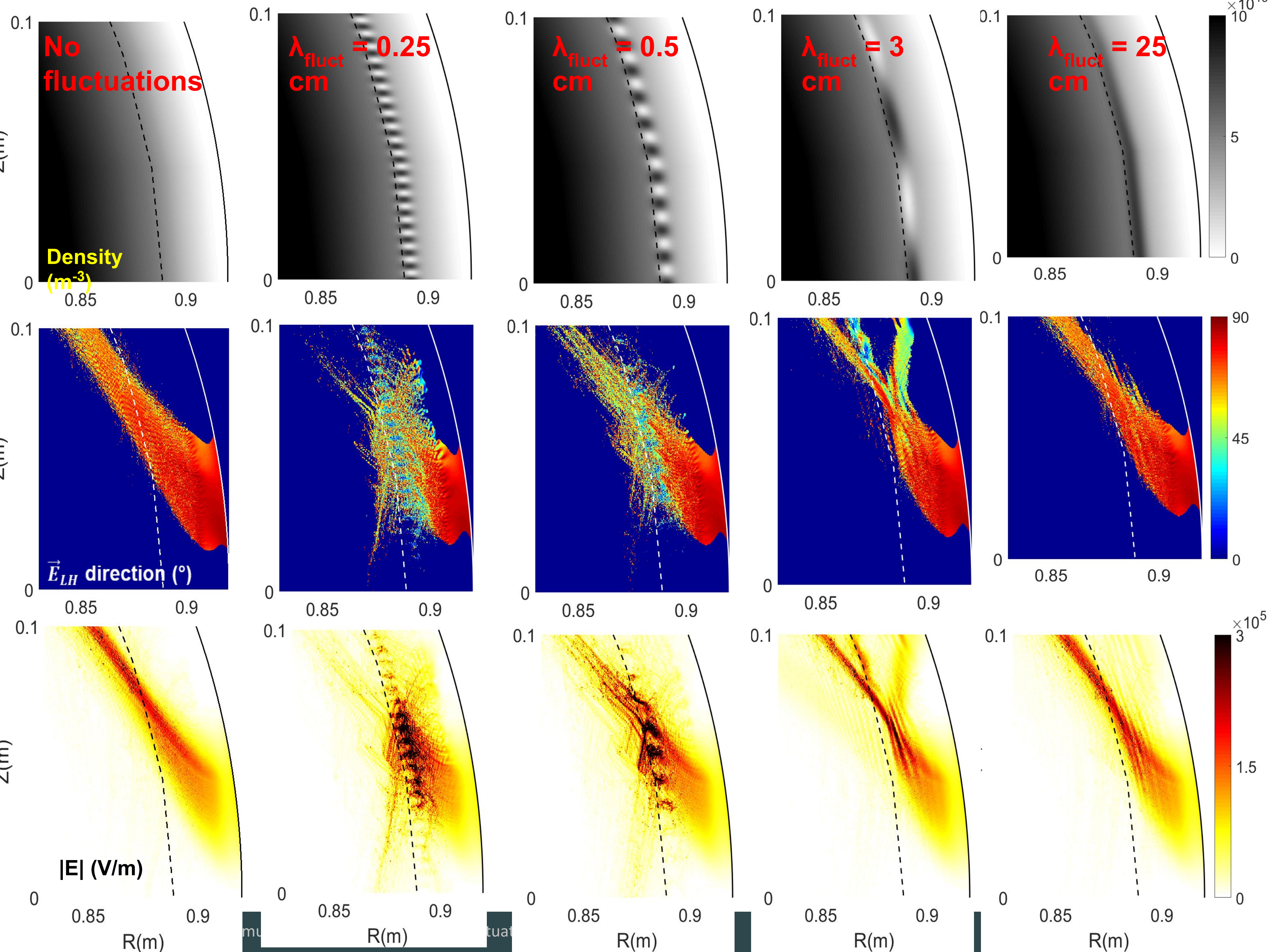
- 2-D cold-plasma full-wave RF simulation with synthetic turbulence show significantly different behavior as a function of fluctuation amplitude ($\tilde{n}/n$) and poloidal wavelength (λ_{fluct})

$$\nabla \times [\nabla \times \vec{E})] - \frac{\omega^2}{c^2}[\overleftrightarrow{\varepsilon} \cdot \vec{E}] = -i\omega\mu_0\vec{J}_{ext}$$

- Example detailed simulation as a function of λ_{fluct} is shown on next slide

- Future SCIDAC work will involve 3-D RF models and replacing synthetic turbulence with a realistic turbulence model such as SOLT3D (see this poster) as inputs into this full-wave model





No fluctuations
λfluct = 0.25 cm
λfluct = 0.5 cm
λfluct = 3 cm
λfluct = 25 cm
Density (m-3)
E_LH direction (°)
|E| (V/m)
R(m)
Z(m)
0.85
0.9
0.1
0
×10^5
3
1.5
90
45
10
5