Update on Scrape-off-layer Transport Modeling

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SIMULATIONS EMPOWERING
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Plasma Profiles in SOL are Important

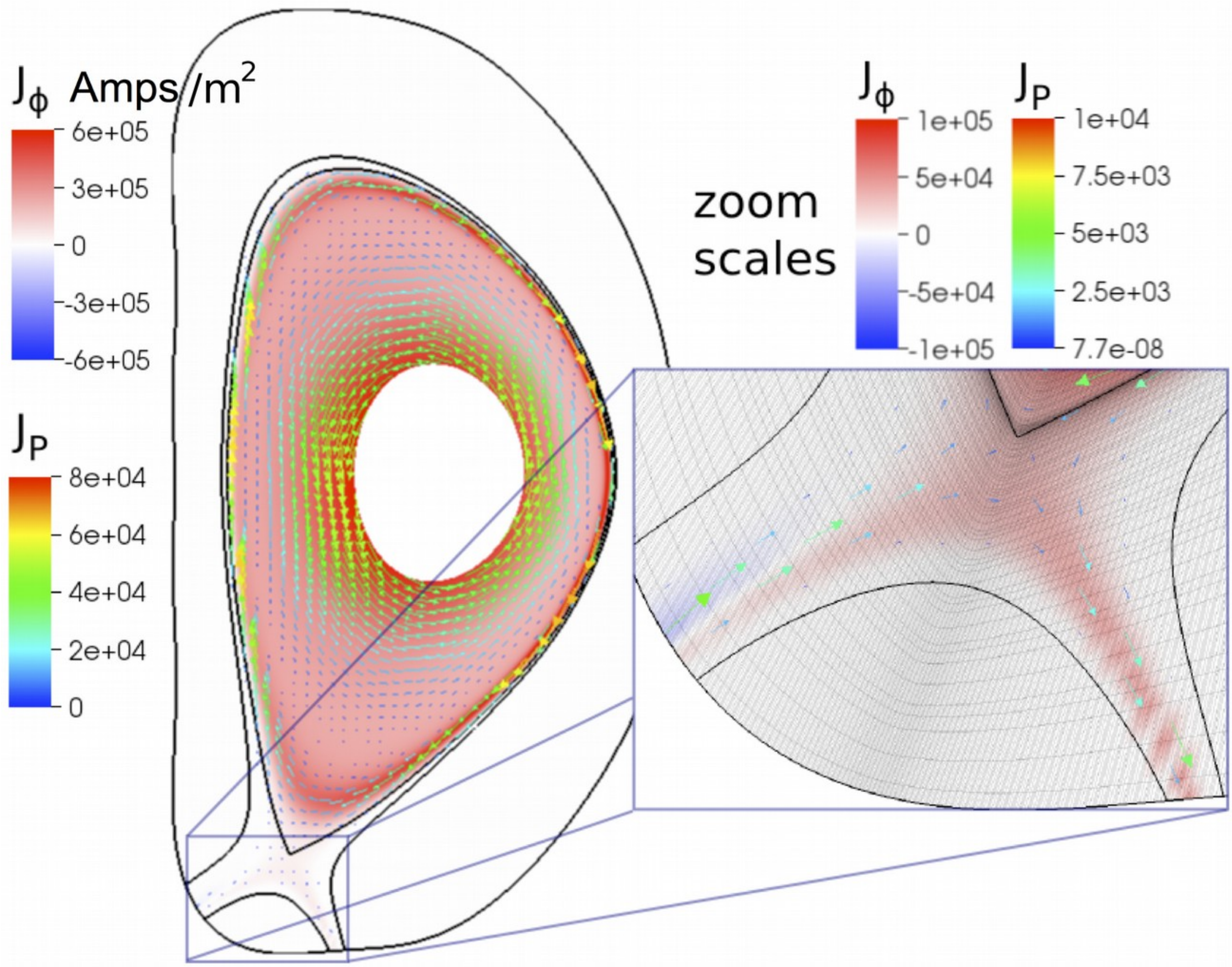
SOL profiles are important because

- **Allow realistic resistivity inside and outsIde LCFS**
- **SOL current profiles can avoid unphysical discontinuities**
- **Details are important for two-fluid, FLR and closures responses**

NIMROD resolves Grad-Shafranov solver to self-consistent currents in open flux region

NIMROD domain includes:

- **Closed-flux region**
- **Scrape-off layer (SOL**
- **Current-free region**



NIMROD for SOL Transport Studies

- **Inclusion of SOL profiles in NIMROD extends the code capabilities for transport studies in SOL**
  - $J \times B = \nabla p$ **force balance in extended MHD does not imply steady states because of flows**
  - **SOL flows due to FLR, two-fluid, and closures responses [A. Aydemir NF 2009; S. Pamela PPCF 2010]**
- **NIMROD studies to investigate these flows and their effects on ELM dynamics are initiated**
  - **Braginskii and (ultimately) DKE-closures for axisymetric transport modeling**
  - **NUBEAM and TORIC in TRANSP and ONETWO for sources**
- **Understanding edge transport key to simulating multiple ELM cycles**

Deriving Near Steady State Solutions

NIMROD solves extended MHD equations

$$\frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{V} = \nabla \cdot D \nabla n$$

$$Mn\frac{\partial \mathbf{V}}{\partial t} = -\nabla p + \mathbf{J} \times \mathbf{B} - \nabla \cdot \Pi_{visc} - \nabla \cdot \Pi_{gv} - \nabla \cdot \Pi_{\|}$$

$$E = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{ne}\left[\mathbf{J} \times \mathbf{B} - \nabla p_e - \nabla \cdot \Pi_e\right]$$

$$\frac{n}{\gamma - 1}\left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T\right) = \mathbf{q} - p \nabla \cdot V + \nabla \cdot n\left[\left(\chi_{\|} - \chi_{\perp}\right)\hat{\mathbf{b}}\hat{\mathbf{b}} + \chi_{\perp}\mathbf{I}\right] \cdot T$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

$$\frac{\partial B}{\partial t} = \nabla \times \mathbf{E}$$

Each field can be written as sum of equilibrium and dynamic components $g(x,t) = g_{eq}(x) + \hat{g}(x,t)$

In general, NIMROD considers equilibrium components evolving on slow time scales and does not evolve them

Steady state equilibrium components imply implicit sources that maintain this solution

- **For equilibrium without background flows, the implicit source for the plasma density can be written as $S_n = -\nabla \cdot D \nabla n_{eq}$**

Deriving Near Steady State Solutions

- **With the source $S_n = -\nabla \cdot D \nabla n_{eq}$, the density equation can be written as**

$$\frac{\partial n}{\partial t} = \nabla \cdot D \nabla n + S_n = \nabla \cdot D \nabla n - \nabla \cdot D \nabla n_{eq}$$

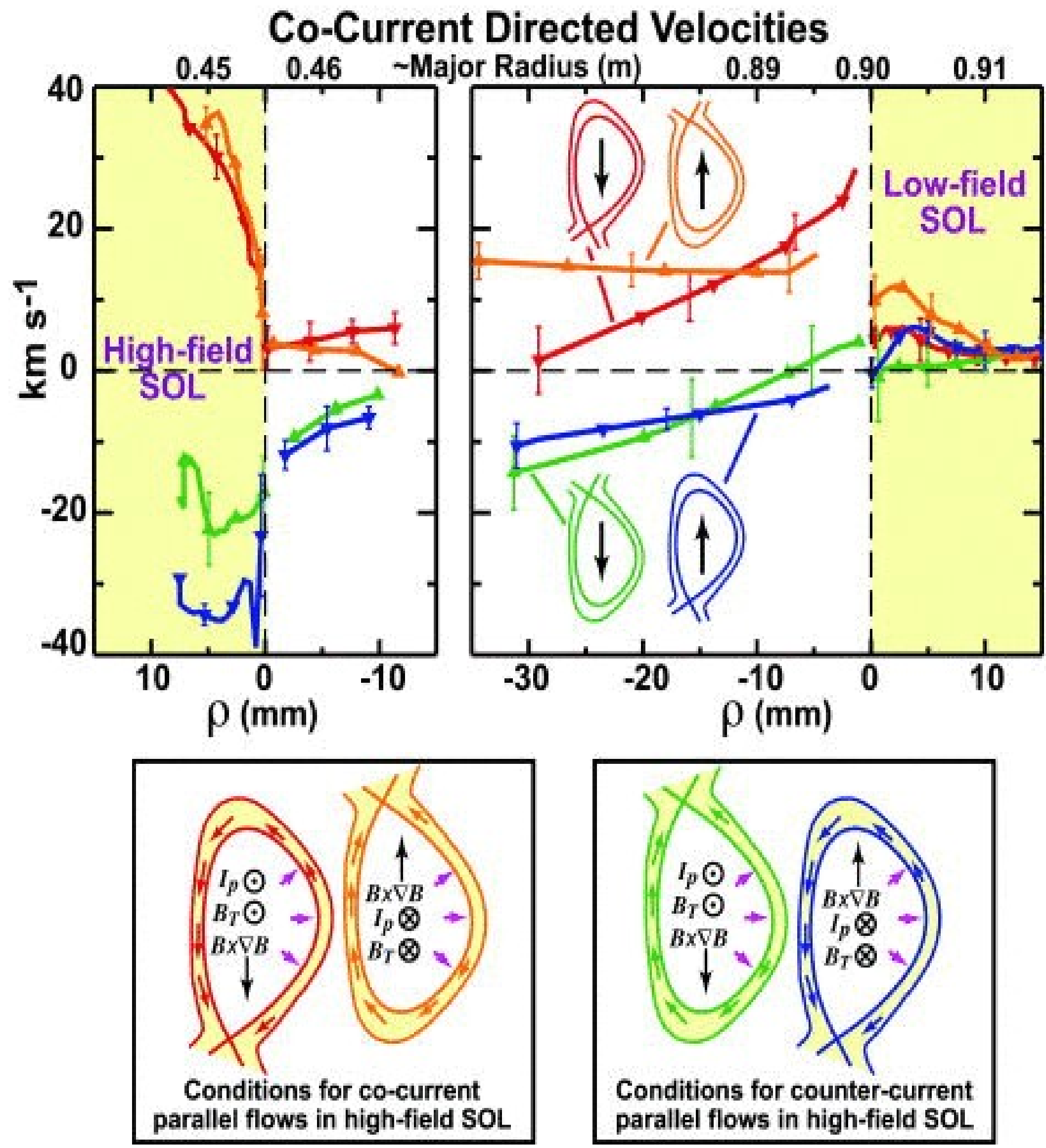
  For steady state, one will get $n = n_{eq}$

- **NIMROD code has an option to transfer equilibrium to n=0 and evolve it in time**
  - **Need to understand impact of sources and models**
- **Hierarchy of MHD models to be considered**
  - **Resistive MHD**
  - **Gyro-viscous resistive MHD**
  - **Two-fluid MHD**
  - **Two-fluid two-temperature MHD**
  - **Braginskii and DKE-closures for axisymetric transport modeling**
- **This study can be used to investigate the physics that determines the SOL flows and SOL width**

SOL Flows are Important for Tokamak Dynamics

Experimental observations of SOL flows in Alcator C-Mod [B. LaBombard PoP'08, NF'04]:

- Near-sonic SOL flows impose cocurrent rotation boundary condition on the confined plasma when B×∇B points toward the active x-point
  - Can be related to eduction in input power needed to attain high-confinement modes
- SOL flows may affect transport and critical gradient values in edge plasma
- SOL flows in L-mode plasma investigated
  - Relation of SOL flows to L-H transition is investigated

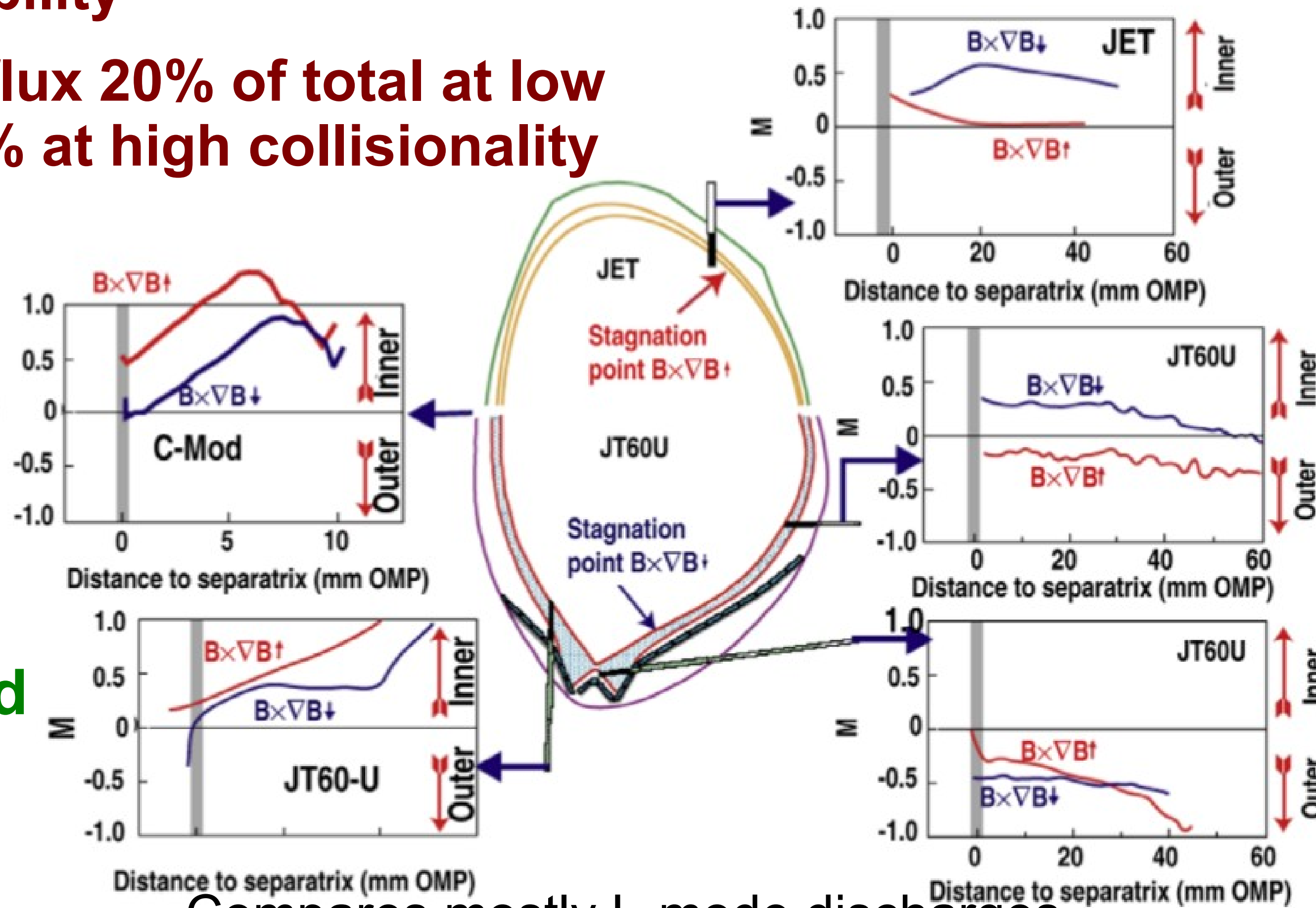


B. LaBombard PoP'08

SOL Flows are Important for Tokamak Dynamics

Multi-device analysis of SOL flows are done by [J. Boedo,JNM'09]

- Radial transport is intermittent and poloidally asymmetric
  - plasma filaments (V_r=1 km/s; L_{pol}=1-3cm) generated near LCFS by interchange instability
  - Intermittent particle flux 20% of total at low collisionality and 70% at high collisionality
- Pressure peak in LFS: pressure asymmetry and Pfirsch–Schlüter currents drive strong SOL flows
- Both L- and H-mode discharges considered

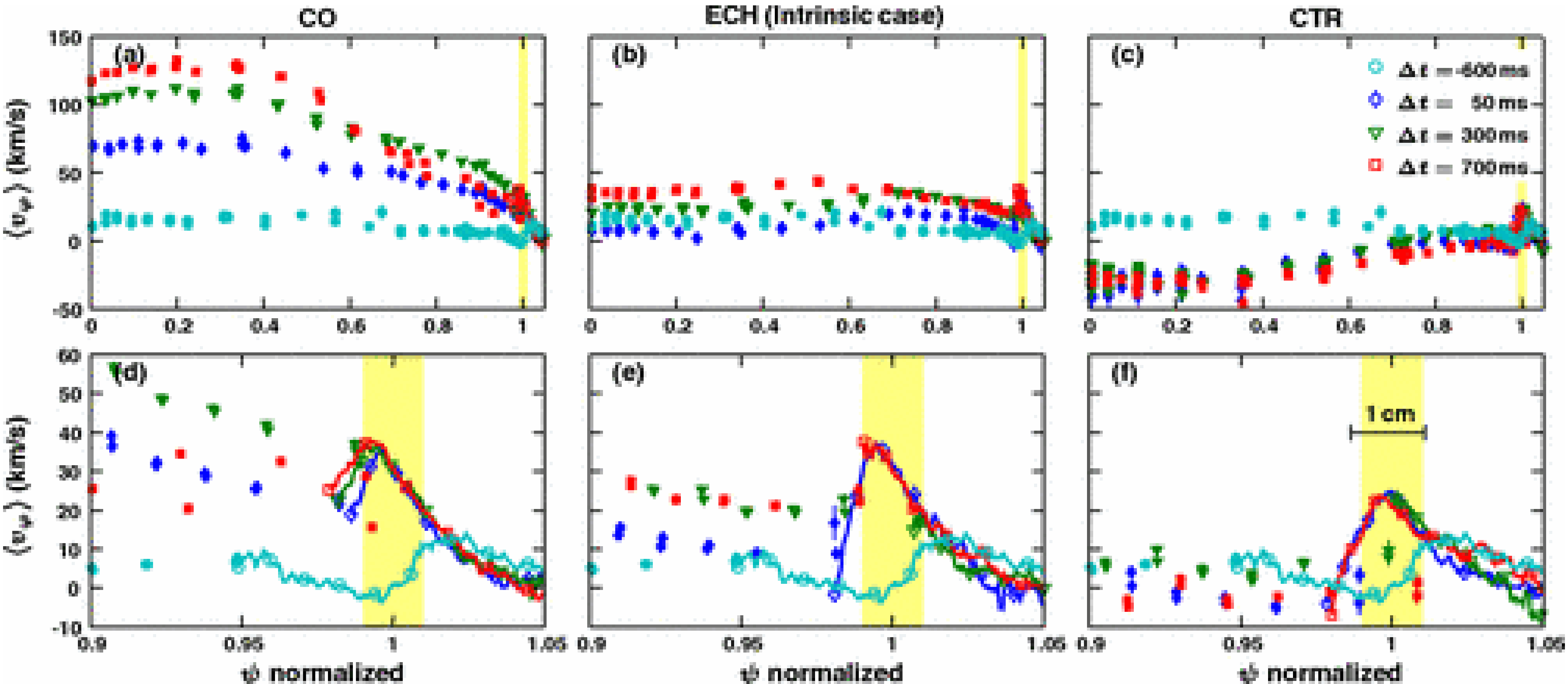


Compares mostly L-mode discharges
J. Boedo,JNM'09

SOL Flows are Important for Tokamak Dynamics

Toroidal flows in SOL also studied for H-mode in DIII-D [S. Müller PRL'11]

- Mostly toroidal flows in the plasma core are considered
- SOL flows provide the boundary conditions for the core flows
  - Strong co-current rotation layer at the separatrix precedes intrinsic rotation development in the core

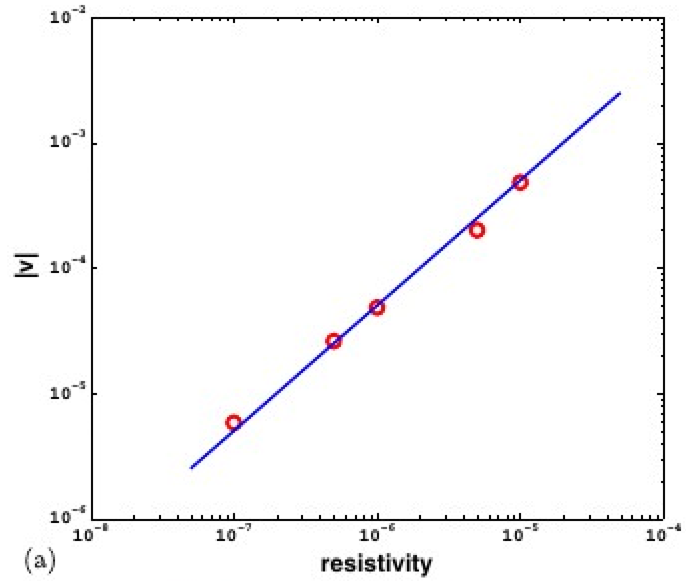


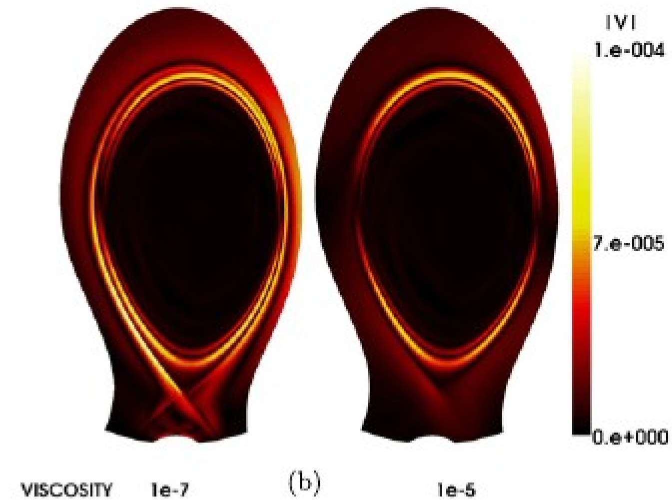
S. Müller PRL'11

Flow studies at the tokamak edge with fluid models

Theoretical/computational fluid studies:

- Aydemir [PoP'07, PoP'09, PPCF'14]
  - SOL flows can be associated with transport processes in a MHD model
  - Resistivity coupled with a bootstrap current model leads to poloidal and toroidal flows, localized to the edge and SOL
  - Analytical derivation and numerical computation using CTD code
- Pamela [PPCF'10] – JOREK
  - Circular and diverted equilibria are studied
  - Dependences on viscosity and resistivity are found
- Ferraro [Thesis'08]
  - Radial, poloidal and toroidal flows are investigated
  - Resistivitity, twp-fluid and FLR effects are separated
- UEDGE? Eric Meier was working on this
- Questions: Is there any real validation?





Dependence of poloidal velocity on resistivity and velocity
S. Pamela PPCF'10

Kinetic studies at the tokamak edge with fluid models

- **Theoretical/computational kinetic studies:**
  - **Boedo/NEO – validation in L-mode [Boedo, PoP'11]**
    - 10x differences in $V_{\parallel}^{D+}$ and V_{tor}^{C6+} ($V_{\parallel}^{D+}$ peaked at ~80 km/sec at midplane)
    - 8-10 times in poloidal asymmetry in $V_{\parallel}^{D+}$ reported
    - NEO modeling works well as long as edge source is modeled
    - Did not include SOL flows because closed sources only
    - Key for validation was to have neoclassical model to relate impurity flow to bulk plasma flow
  - **XGC0**
    - No validation studies that we are aware of

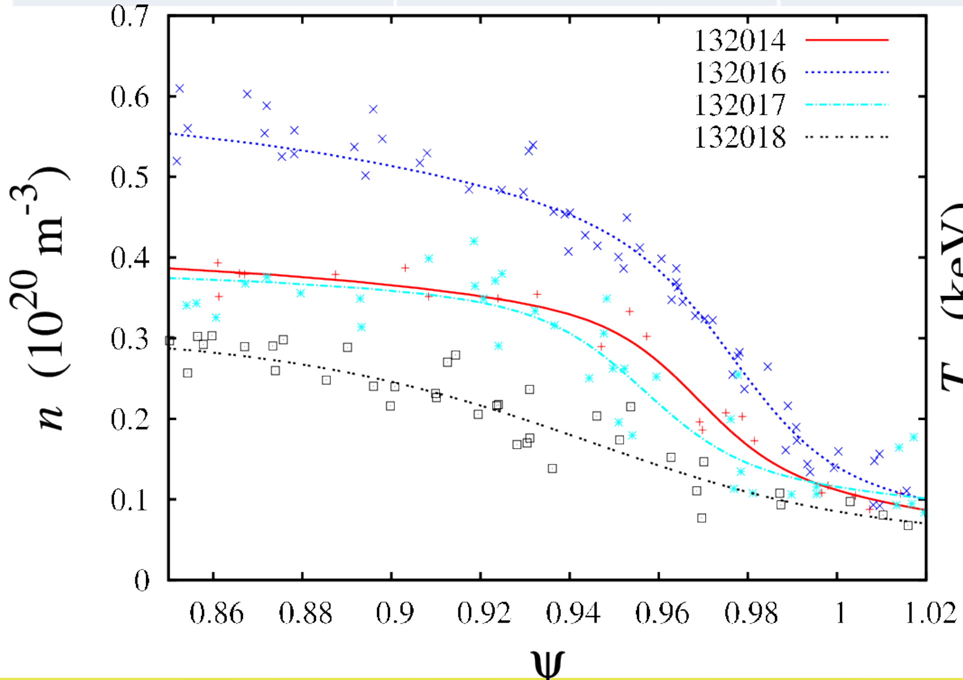
SOL Width Modeling has not yet used eMHD capabilities

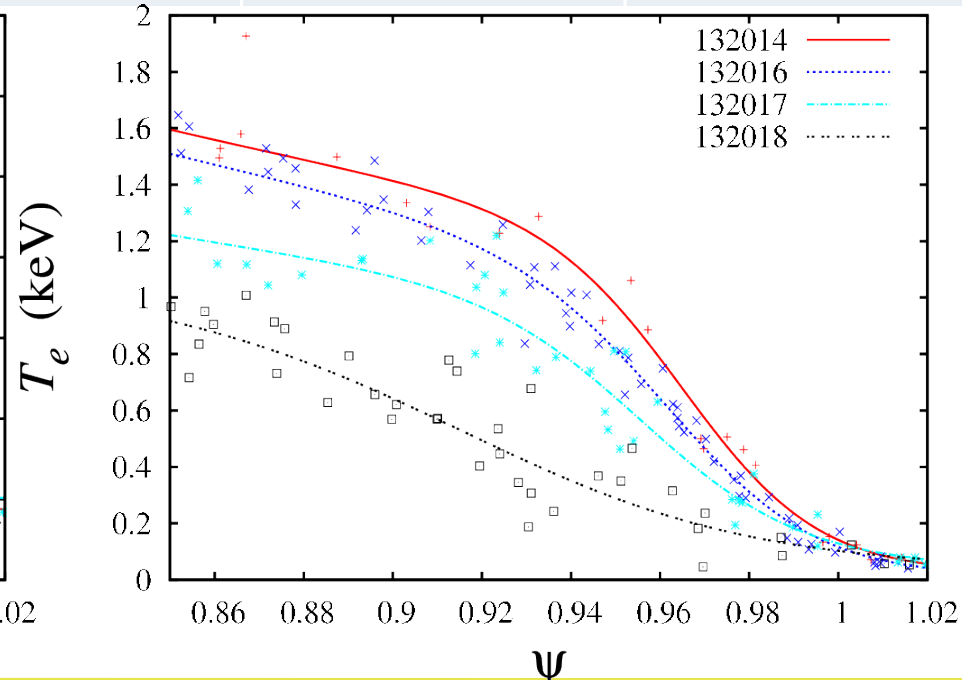
- Understanding the physics of SOL width is important because the existing scalings are very unfavorable for ITER
  - It is important to understand the processes that control the SOL width in order to develop mechanisms to control it
- Most models for SOL width are neoclassical- or anomalous based models
  - Heuristic neoclassical model that estimates the SOL width from the balance of magnetic drifts and near sonic PS flows out of SOL to the divertor plates [Goldstone NF'12]
  - In anomalous transport models, SOL width is determined by a balance between parallel transport and cross-field turbulent transport [Myra PoP'15; Halpern NF'13]
  - Fluid modeling with UEDGE code often uses models for source/fluxes to give agreement with heuristic models
  - XGC0 based model [Pankin PoP'15] also needs “sub-grid model” for transport fluxes but has neoclassical effects included
  - Extended MHD+DKE closure attractive
    - Force-balance self-consistency

Experimental Current Scan on DIII-D

- **Four reference DIII-D discharges with four different plasma currents (0.51-1.5MA)**
- **[Snyder *et al*., PoP 16 (2008) 056118; Groebner *et al*., NF 49 (2009) 085037]**
  - **The discharges have about the same**
    - **toroidal magnetic field (2.1 T)**
    - **plasma shape (average triangularity 0.55)**
    - **normalized toroidal beta (β_n ~ 2.1-2.4)**

Discharge	132016	132014	132017	132018
Time, msec	3023	3023	2998	1948
I_p, MA	1.50	1.17	0.85	0.51



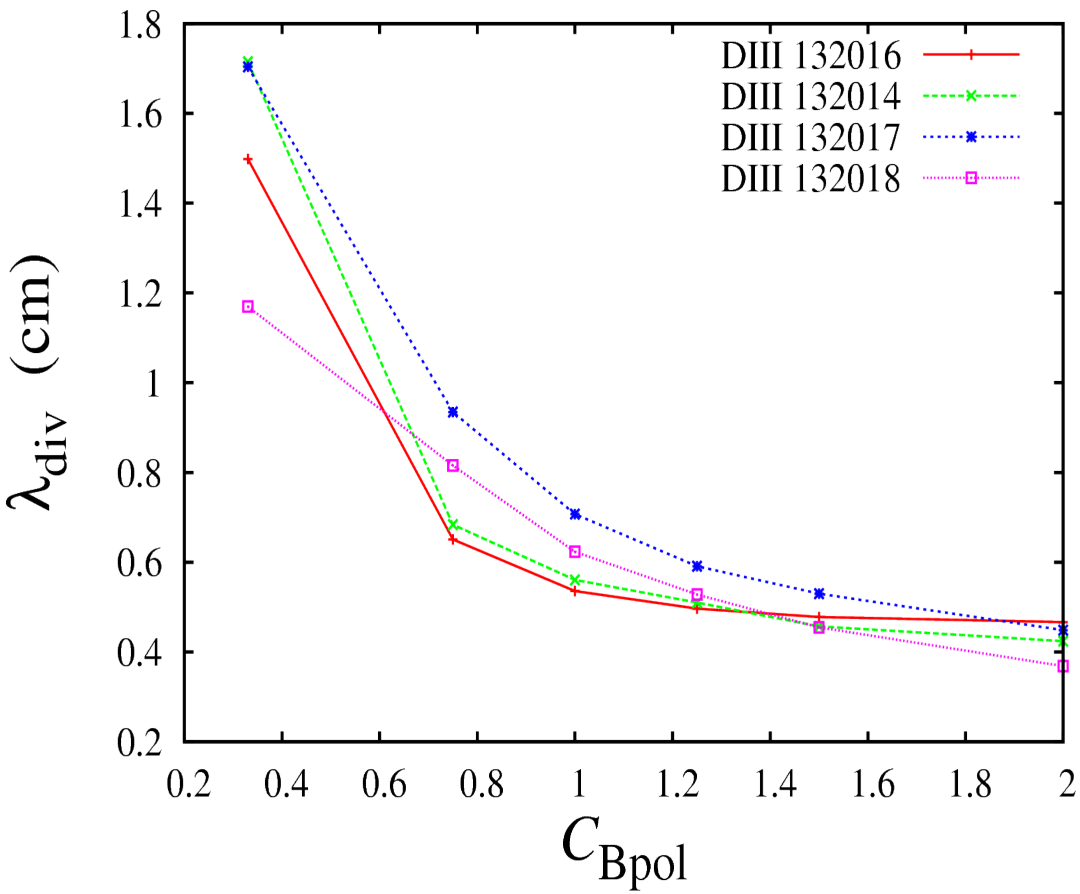


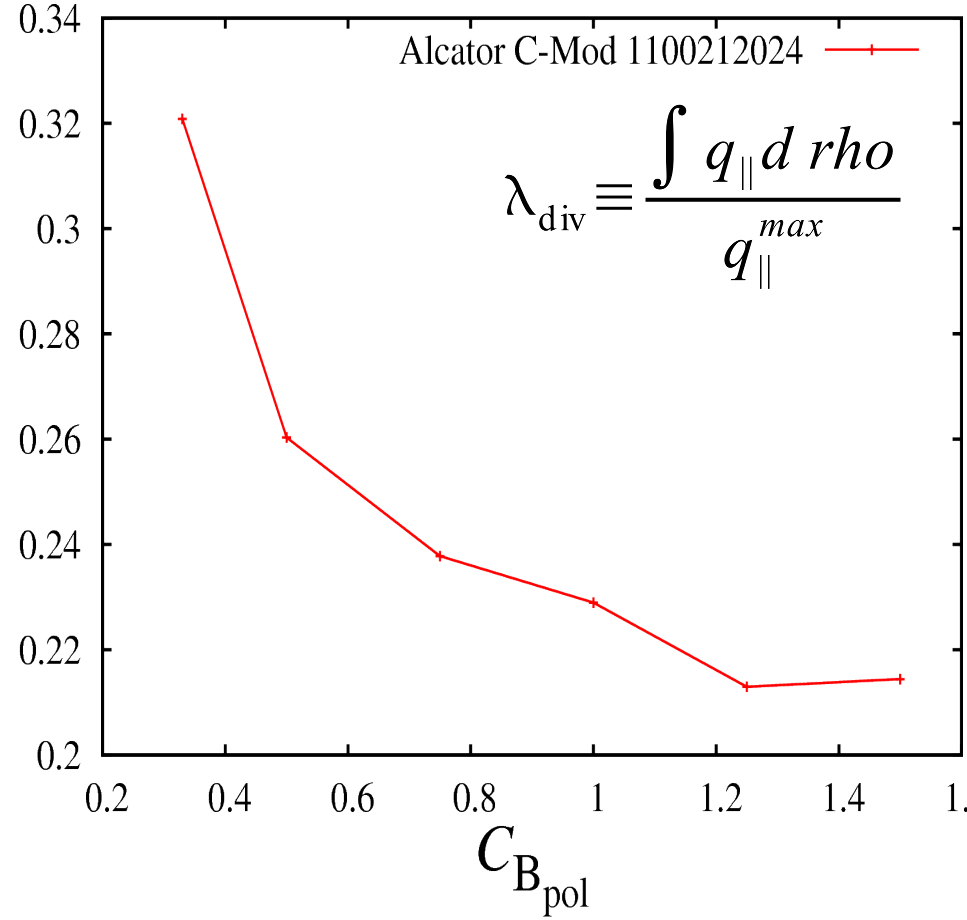
XGC0 Kinetic Edge Code

- XGC0 code is developed for long time simulation of kinetic equilibrium and transport
  - 5D Lagrangian guiding center dynamics
  - Axisymmetric solution for radial electric field *Er*
  - Ion/electron/neutral, full-f
  - Zeff in the version version used for this study
  - Momentum-energy-particle conserving Monte-Carlo collisions
  - $\Phi(\psi)$ electric potential solver
  - XGC0 is being integrated with all the other physics components
  - XGC0 evaluates kinetic bootstrap current, and reconstruct the Grad-Shafranov equilibrium
  - Simple anomalous transport model that is based on a modified random walk algorithm

XGC0 evaluated Neoclassical Heat Load Width is Broader at Smaller Plasma Currents

Four DIII-D discharges and one Alcator C-Mod discharge 1100212024 that was a part of Alcator C-Mod/DIII-D similarity campaign analyzed → $\lambda_{div} \propto I_P^{-0.8}$ for DIII-D

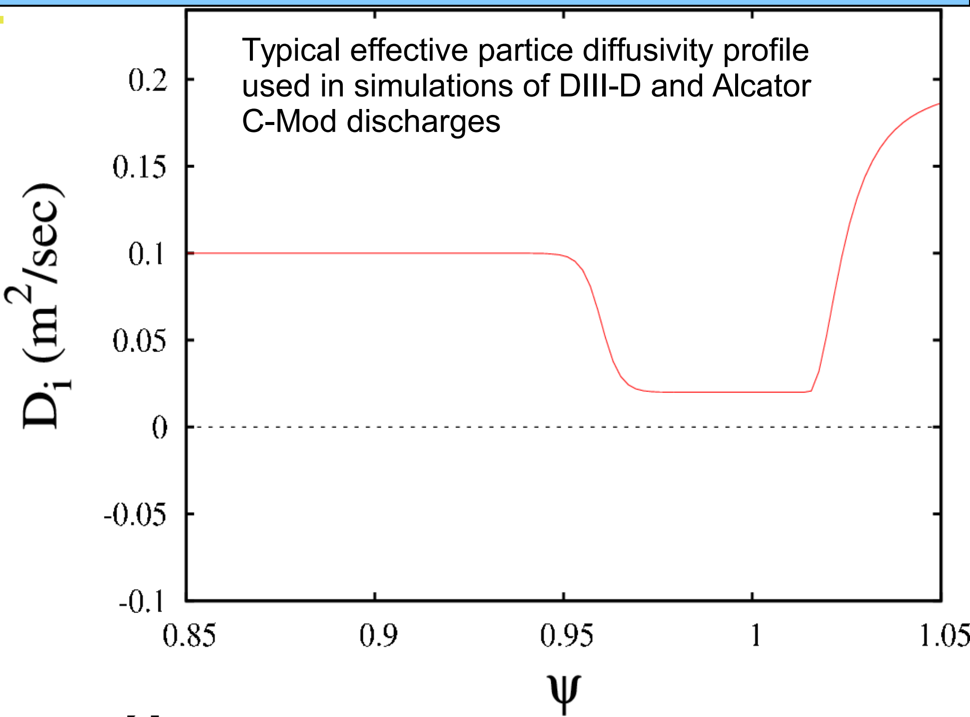


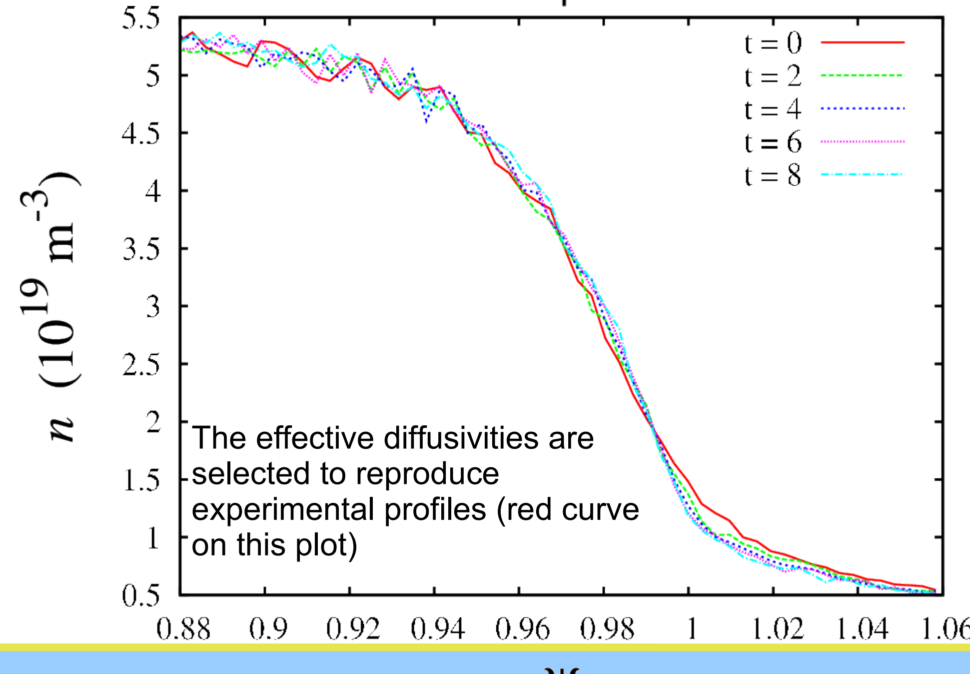


C_{Bpol} is a scaling factor in XGC0 for poloidal flux, hence plasma current

Anomalous transport found from XGC0 analysis

- While the reduced-theory-based models for anomalous transport in XGC0 are available, in these heat load studies the XGC0 simulations use anomalous effective diffusivities that are intended to reproduce experimental profiles
  - Alcator C-Mod and DIII-D discharges were analyzed
  - It has been found that strong pinches in all channels of anomalous transport were necessary to reproduce experimental profiles
- To begin with, anomalous diffusivity profiles are kept fixed and assume to be poloidally uniform for each discharge in all the I_p scans





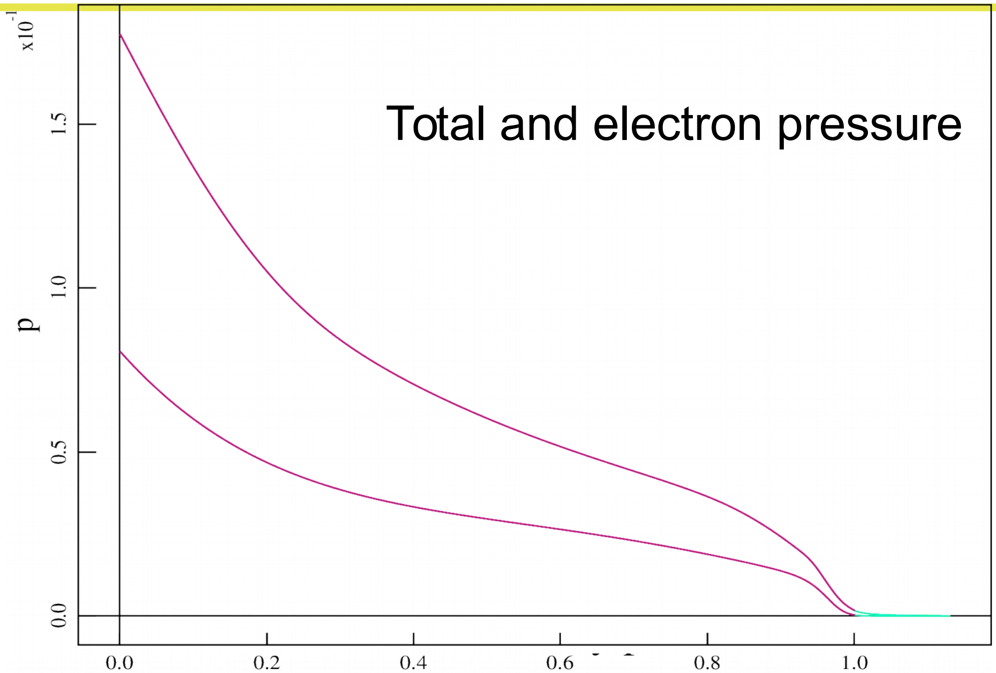
Conclusions from SOL Width Studies with XGC0

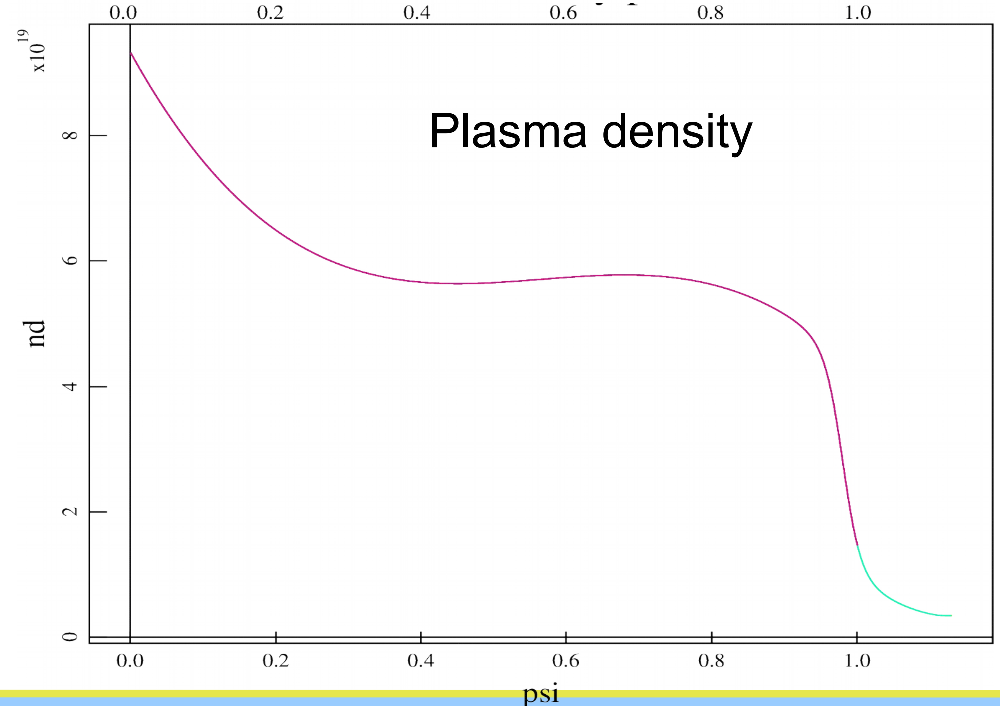
Progress in understanding divertor heat load width is presented using XGC0 particle code

- Neoclassical divertor heat load width is found to be broader for smaller plasma currents $\propto I_P^{-0.8}$ in DIII-D
- Alcator C-Mod discharge has weaker scaling of the divertor heat load width with plasma current compared to four DIII-D discharges analyzed in this study
- Neutral collisions have rather weak effect on the neoclassical divertor heat load width.
- A poloidally uniform, Ip-independent anomlous transport can destroy the neoclassical Ip scaling behavior.
- However, a ballooned, even Ip-independent, anomalous transport can recover the neoclassical Ip behavior $\propto I_P^{-0.6}$
- Did not include analysis of flows in these experimental studies

SOL Flow Modeling Using NIMROD

- DIII-D discharges that were used with XGC0 are also used with NIMROD
- Several MHD models are tested so far for the high plasma current DIII-D discharge 132016
  - Resistivity is scaled by a factor 10^4
  - Effect of resistivity profile is studied
  - Gyroviscosity and two effects are investigated
  - All simulations shown use anisotropic parallel momentum and thermal conduction!
- EFIT equilibrium and reconstruction of experimental density and temperature profiles are used
  - Zeff=1.1
  - Spitzer resistivity
  - $S=1.5 \cdot 10^9$
  - $\tau_A=4.7 \cdot 10^{-7}$ sec
  - $\tau_R=6.9 \cdot 10^2$ sec

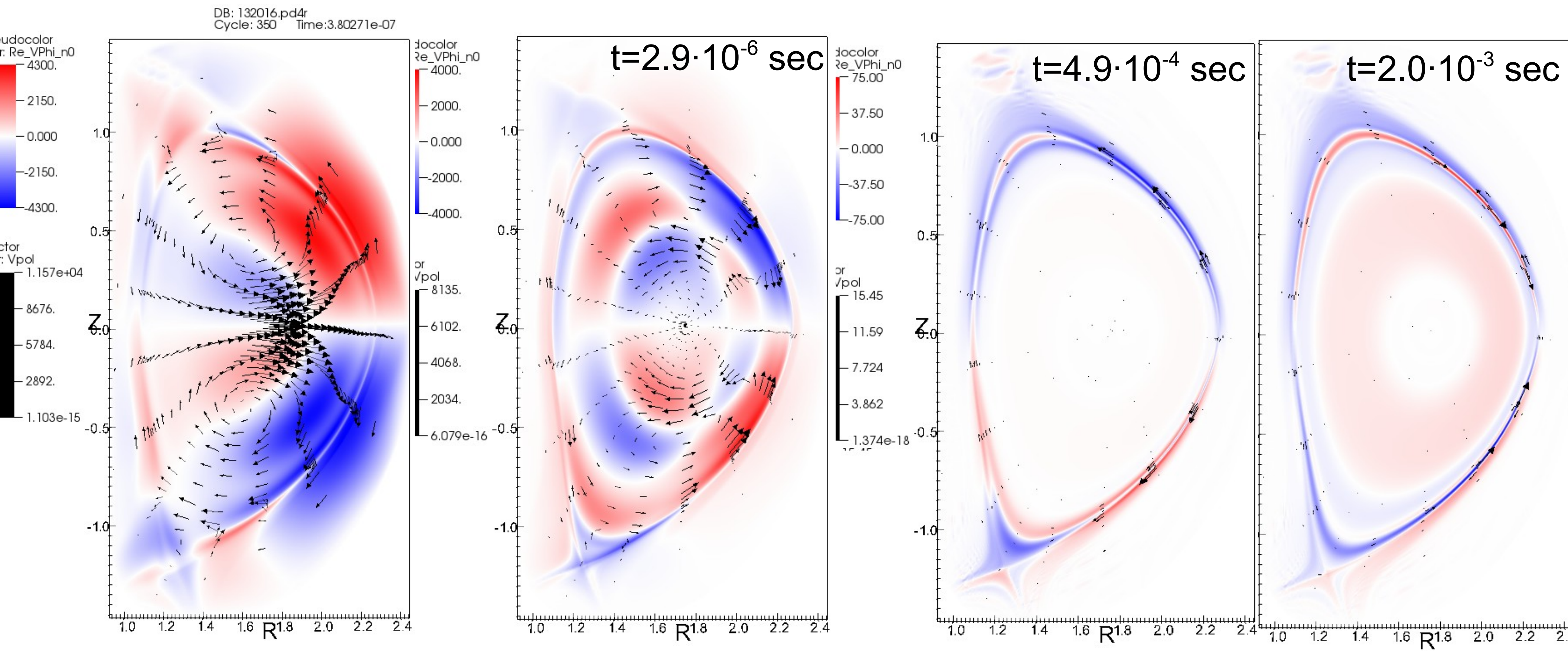




Evolution of Flows in DIII-D Discharge 132016

equilibrium transferred to n=0 mode and evolved

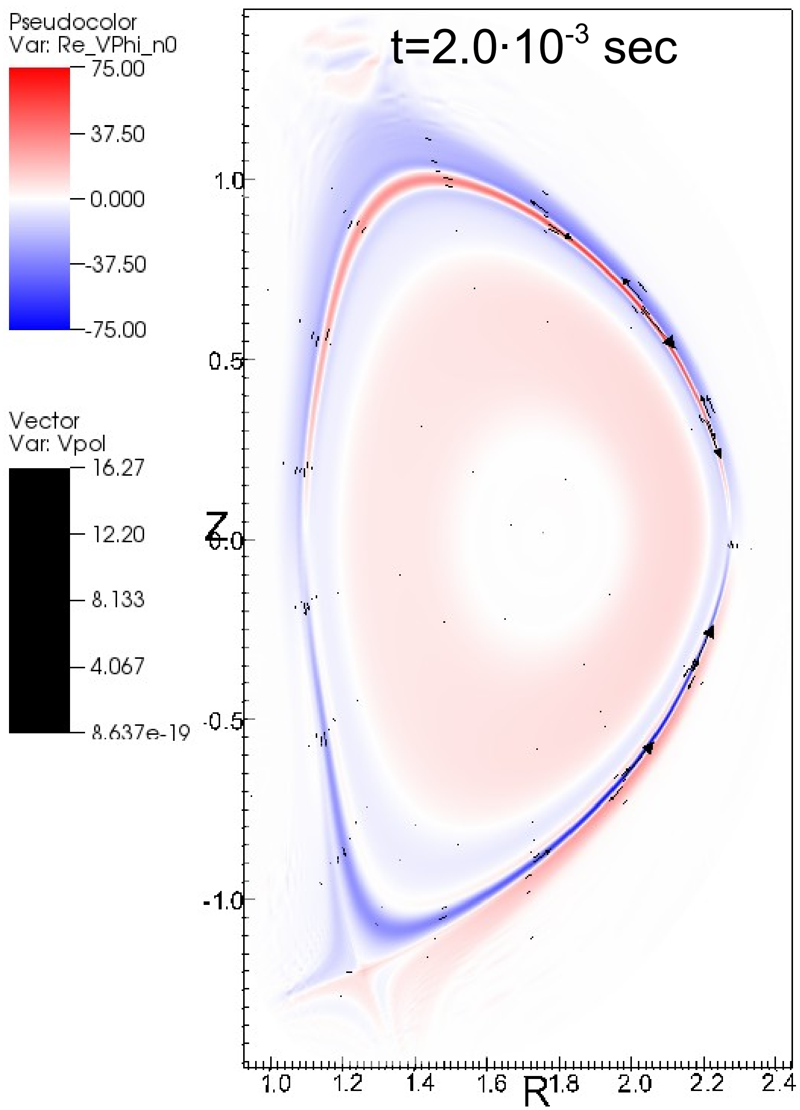
- No severe requirements to resolution: 60x128 with pd=4
- 96 cores on Edison are utilized

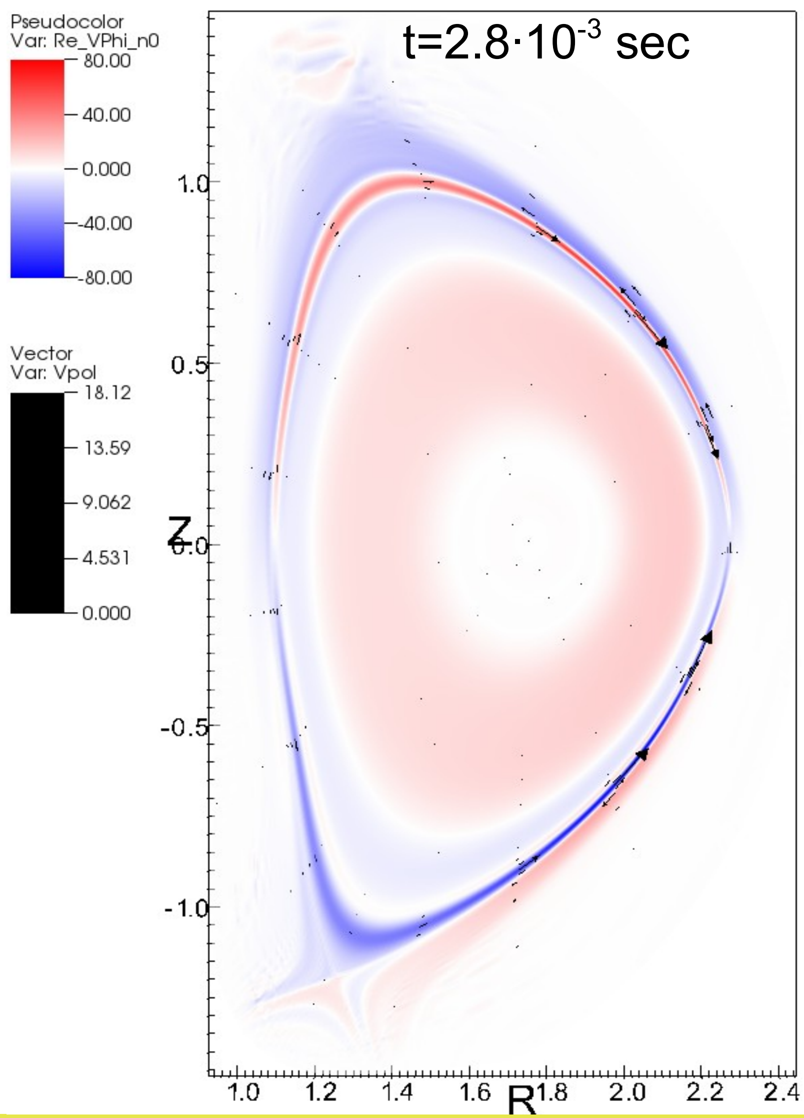


Evolution of Flows in DIII-D Discharge 132016

Resistivity is found too small to see any effect

- Spitzer resistivity profile vs flat resistivity profile at S~10^9

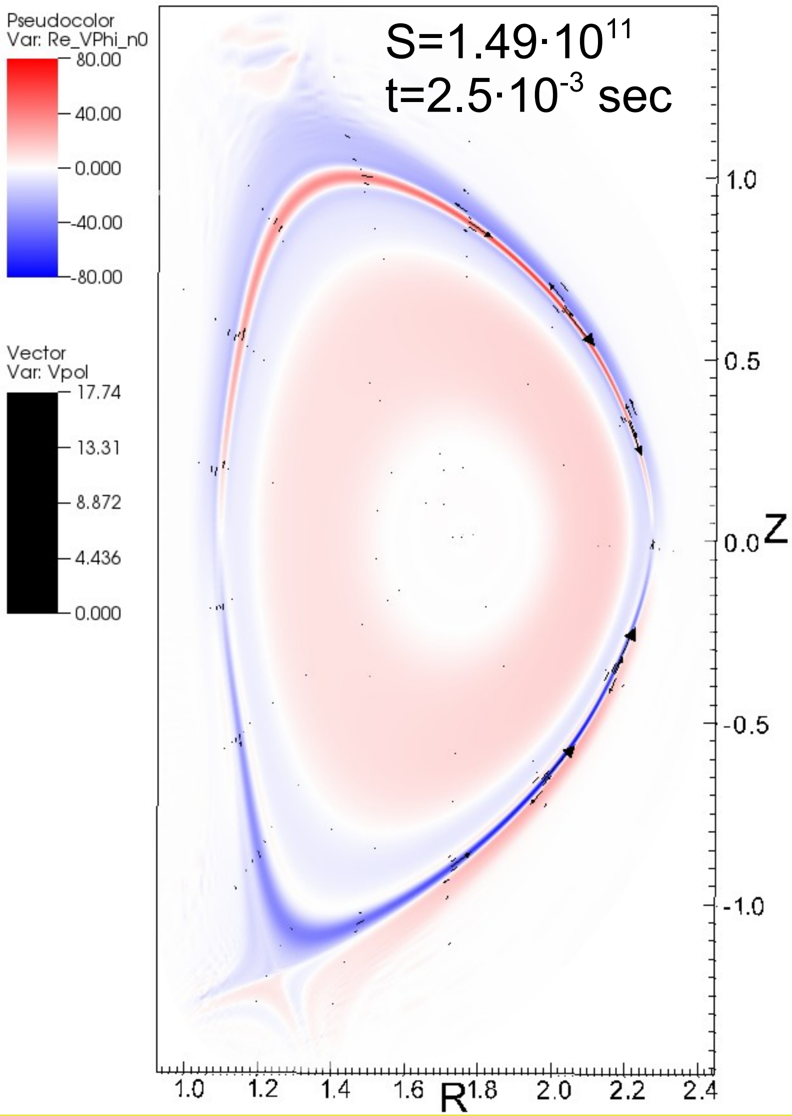


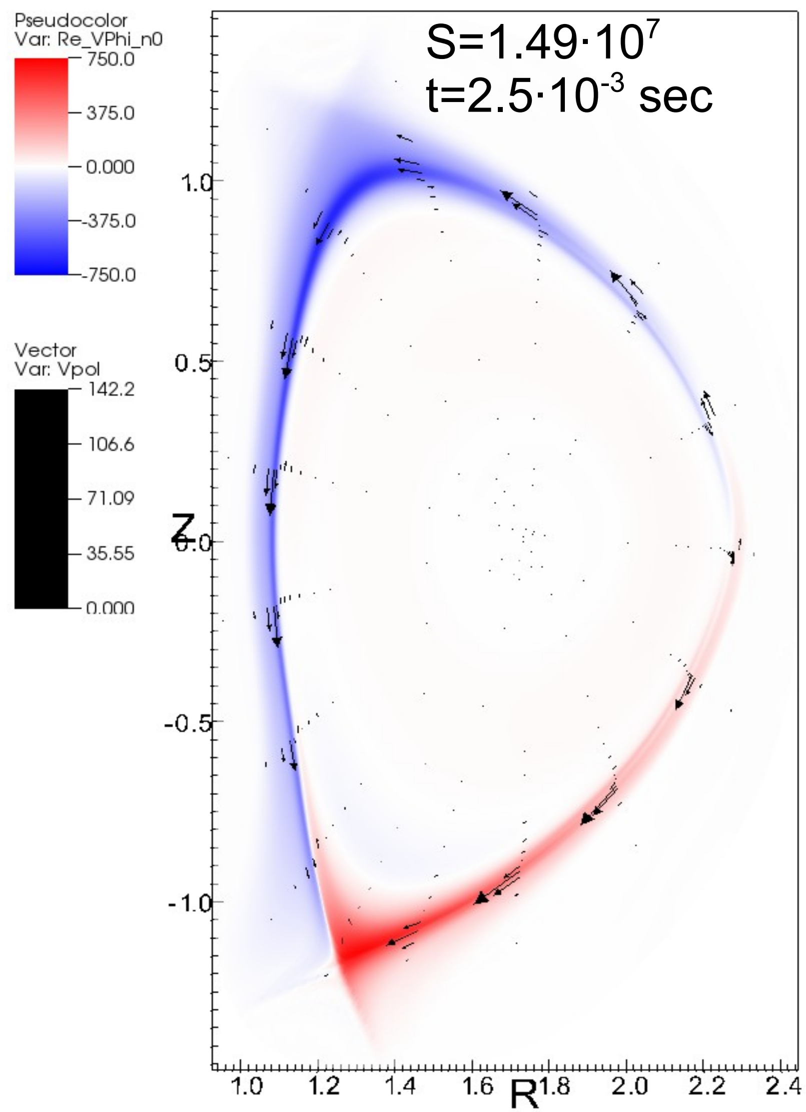


Evolution of Flows in DIII-D Discharge 132016

Resistivity is scaled so S changes from $1.5 \cdot 10^7$ to $1.5 \cdot 10^{11}$

– **$S \sim 10^7$ results in 10x flow magnitude => Realistic values required**

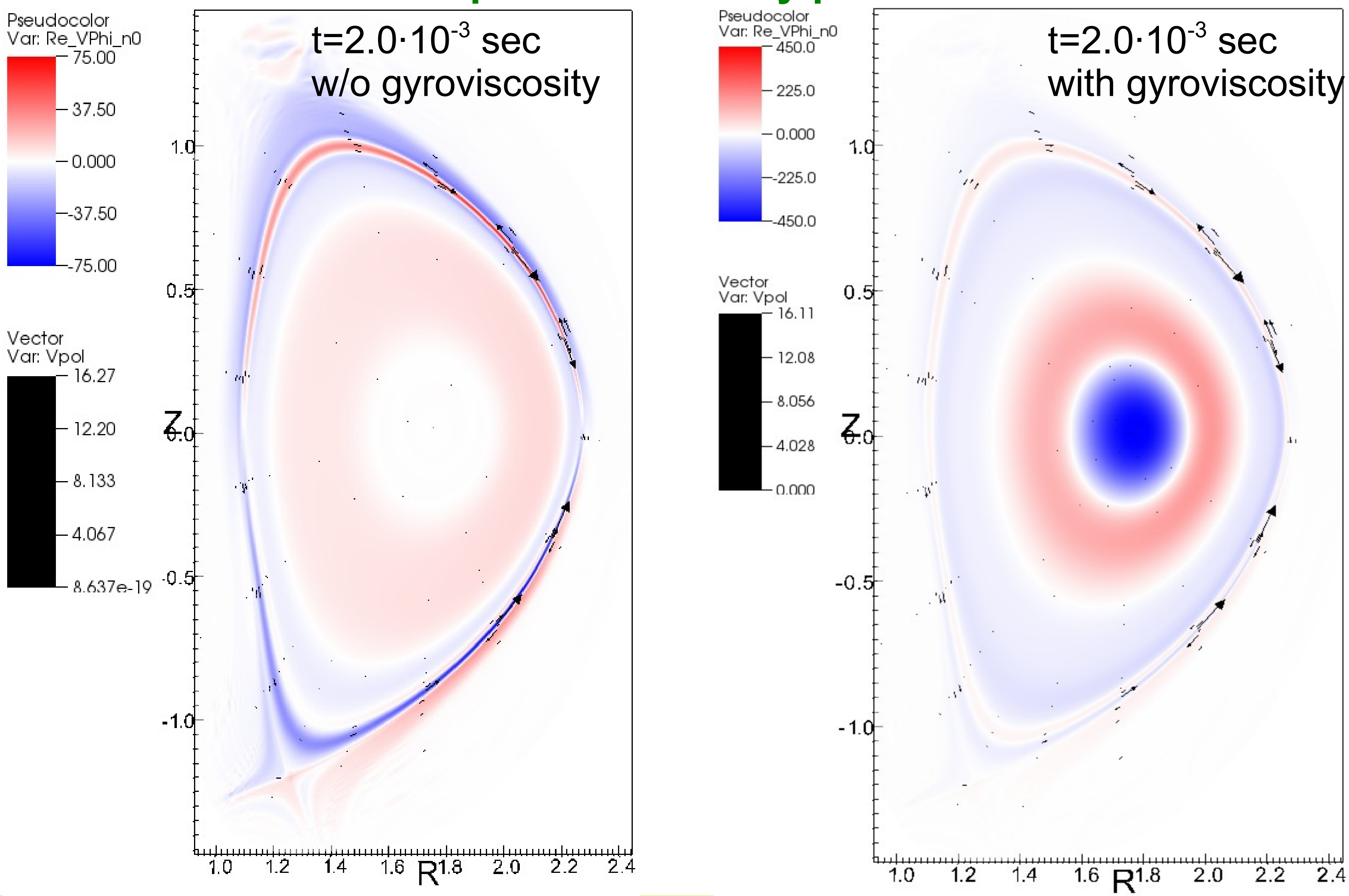




Evolution of Flows in DIII-D Discharge 132016

Effect of gyro-viscosity is tested

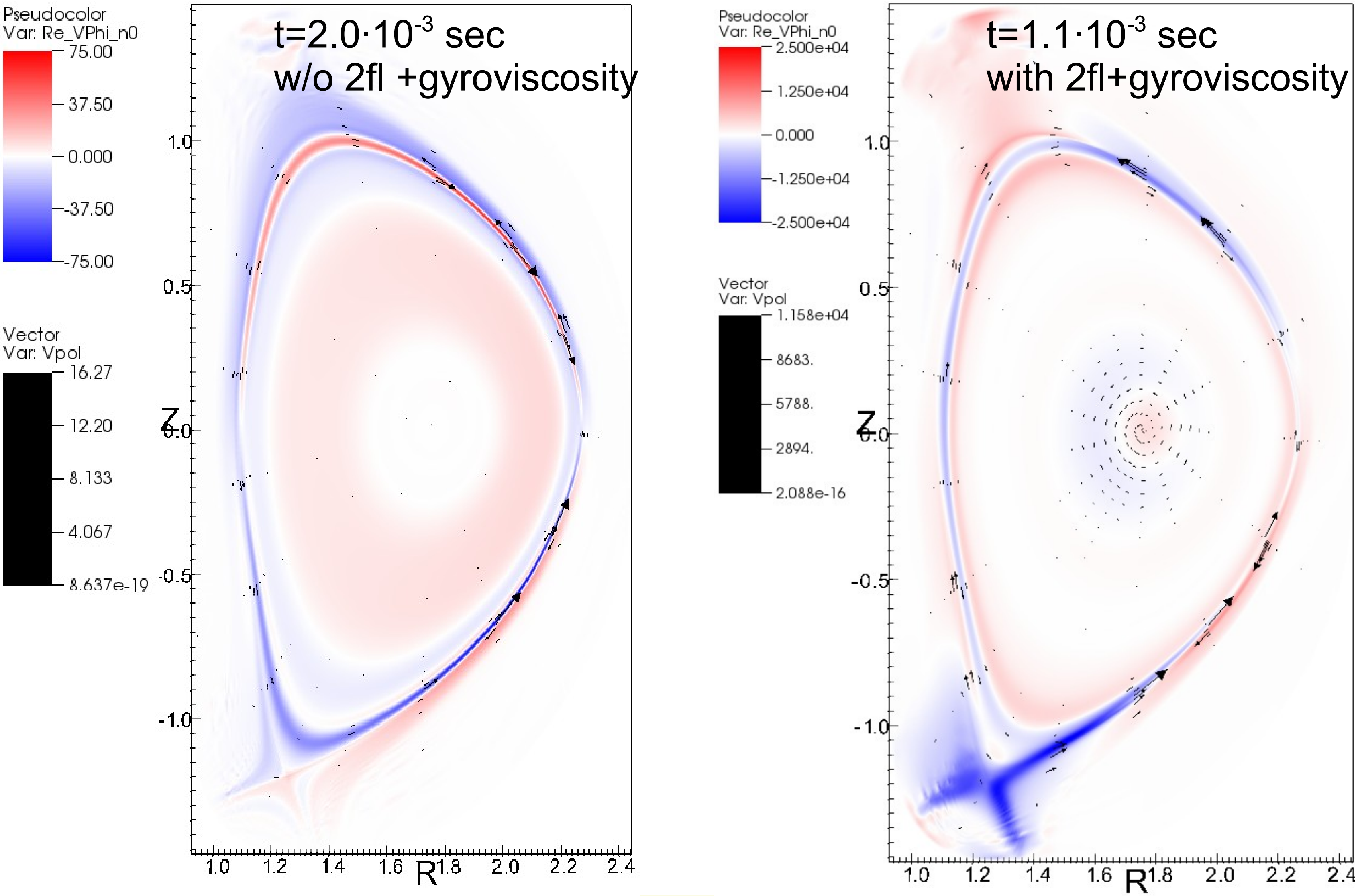
- **Strong Toroidal velocity profiles in plasma core observed**
- **Small effect on the poloidal velocity profiles**



Evolution of Flows in DIII-D Discharge 132016

Two-fluid and gyroviscosity effects

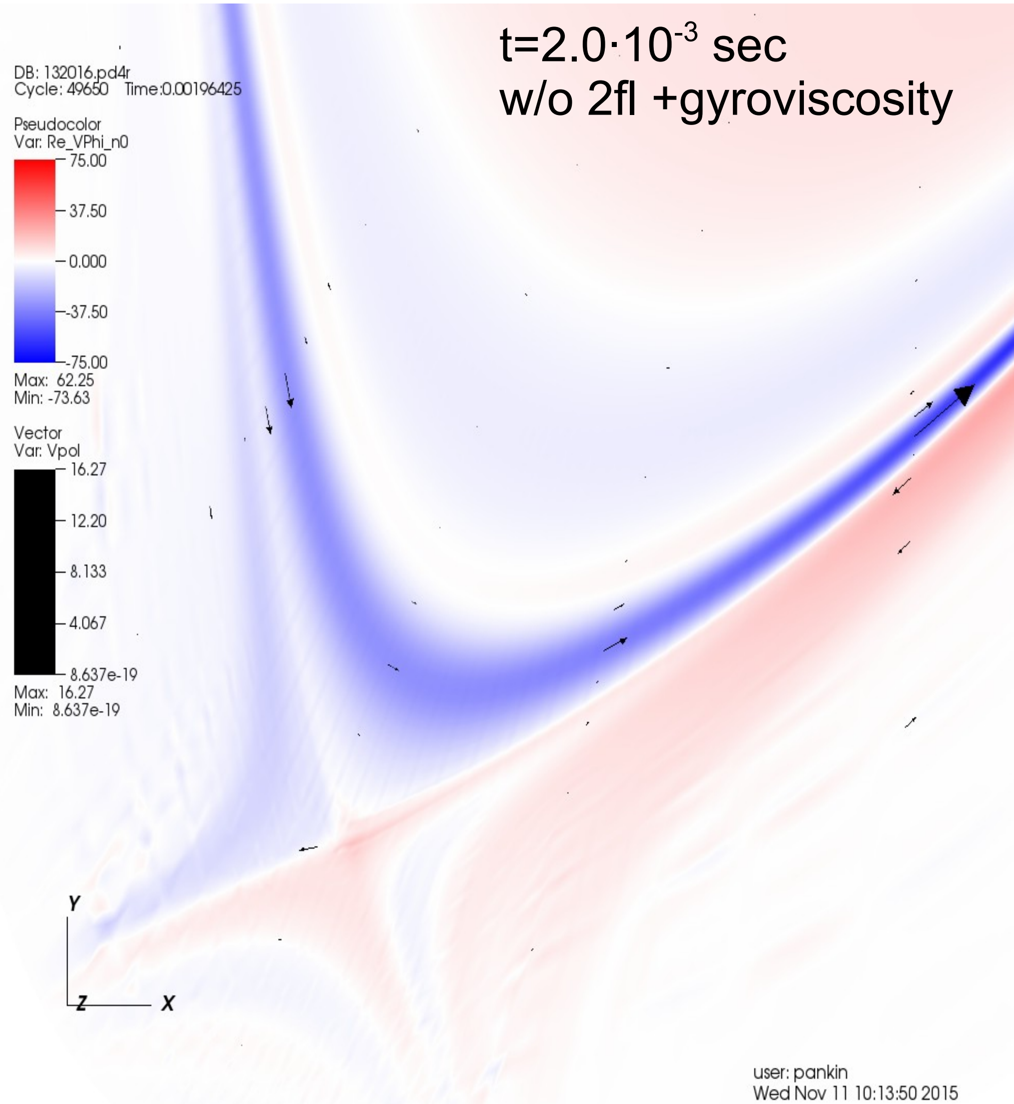
- Toroidal and poloidal velocities are enhanced
- Noticeable poloidal rotation in the plasma core

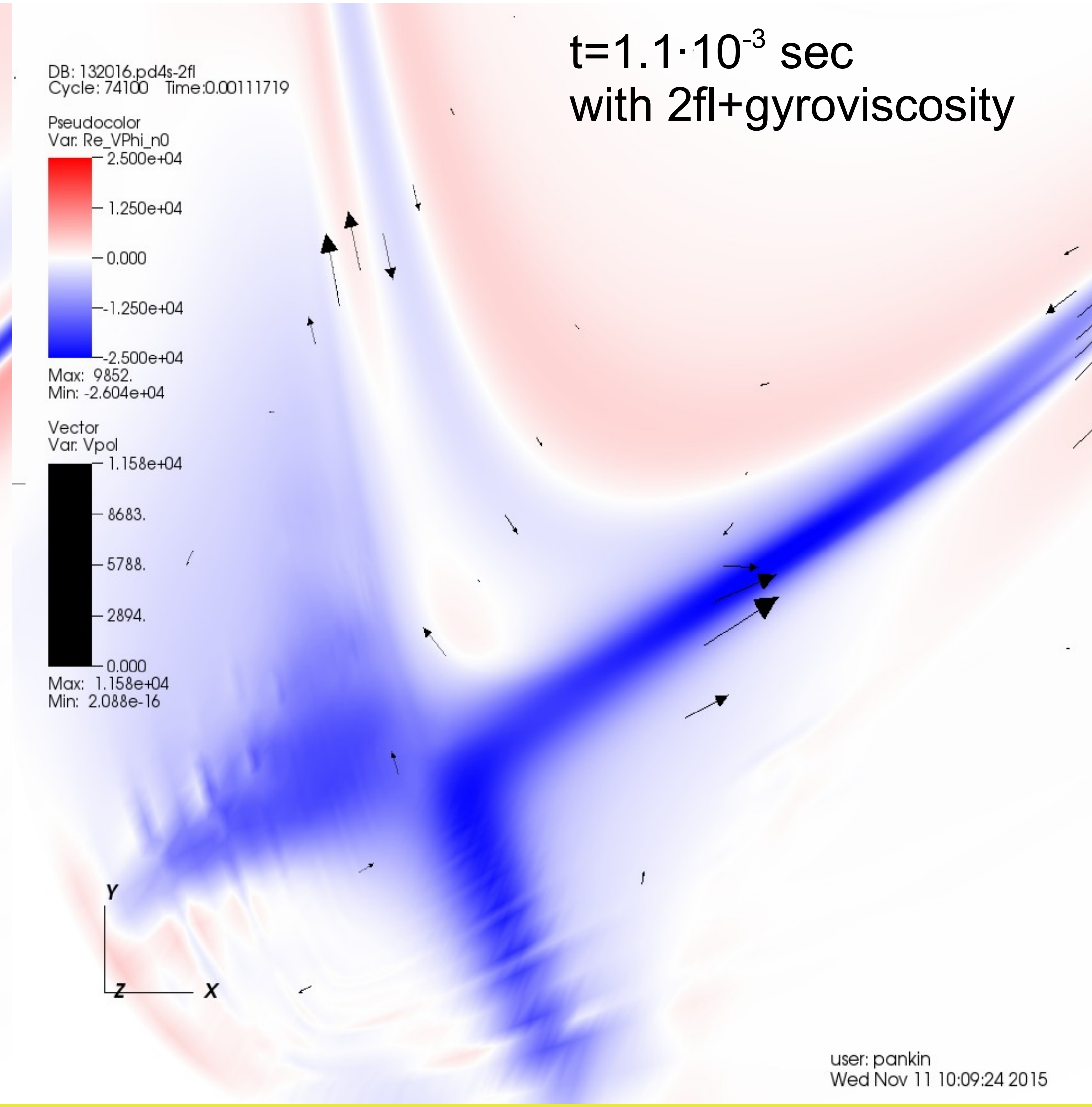


Evolution of Flows in DIII-D Discharge 132016

Two-fluid and gyroviscosity effects

– Two-fluid simulations might require a better resolution





Summary

- NIMROD code is used for transport modeling of velocity profiles in SOL of DIII-D discharges
- For experimental relevant plasma profiles of DIII-D discharge 132016
  - Resistivity gradient is found to have little effect on the poloidal and toroidal rotation profile at realistic values
  - 100x resistivity results in 10x poloidal fluxes in SOL
  - Gyro-viscosity is found to increase the toroidal rotation in the plasma core
  - Two-fluid effects are found important both for toroidal and poloidal flows
  - Two-fluid effects enhance the SOL poloidal flows by 1000x compared to poloidal flows computed using resistive MHD
- Inital results are confusing and more analysis is needed
  - Lots to do: Boundary conditions, diffusivity profiles, DKE, ...
  - Need to calculate the widths as a post-processing diagnostic

Current Capabilities in NIMROD Relevant to ELMs

- **Physics basis [C.Sovinec JCP 2004]**
  - Complete Braginskii formulation is implemented
    - Hall term, gyroviscosity, ion parallel stress tensor [C.Sovinec JCP 2010]
    - Dissipation terms: resistivity, viscosity, thermal and particle diffusivities
  - Choice of closures: Braginskii, kinetic PIC [C. Kim PoP 2008], and continuum electron and ion drift-kinetic [E. Held PoP 2015]
    - Options to include neoclassical effects and ion orbit losses
  - NIMEQ [Howell CPC 2014] and FGNIMEQ [to be submitted] Grad-Shafranov solvers for pre-processing the experimental data
  - Modeling of neutrals is being implemented [Shumlak, U-Wash]
- **Code development and performance improvements**
  - Improvements of preconditioning options
  - Convergence of interchange modes [C. Sovinec to be submitted to JCP]
  - Scaling up to 65,000 cores
  - Development of selection of global and local upwinding schemes
  - Implementation of parallel hdf5 IO
- **Improvement of visualization capabilities**
- **Verification and validation studies**

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