Modeling of Edge Localized Modes in KSTAR Tokamak Using the Extended MHD NIMROD Code

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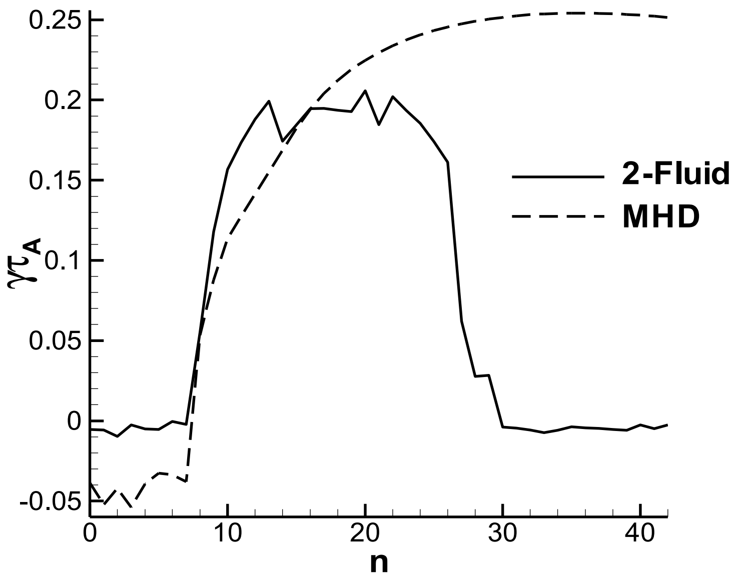
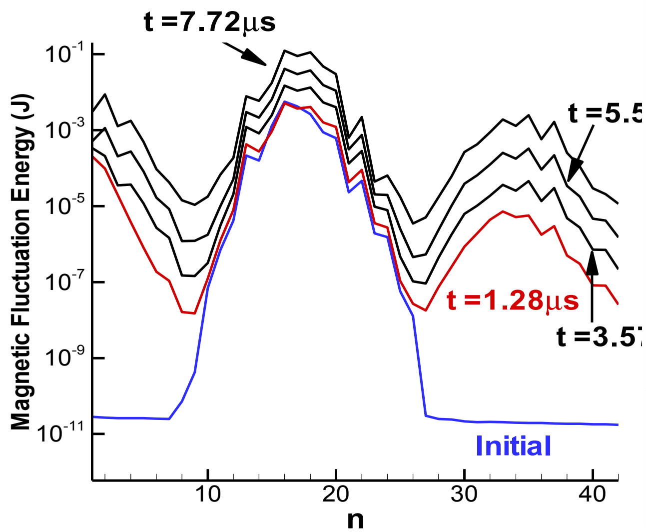
SIMULATIONS EMPOWERING YOUR INNOVATIONS

Previous Modeling of ELMs Using NIMROD

- **Linear and nonlinear ELM dynamics in DIII-D have intensively investigated using the NIMROD code 10 years ago [C.Sovinec IAEA 2006; A. Pankin PPCF 2008]**
- **Valuable results were obtained**
  - **Two-fluid and FLR effects are found to stabilize large toroidal mode numbers in linear and nonlinear simulations**

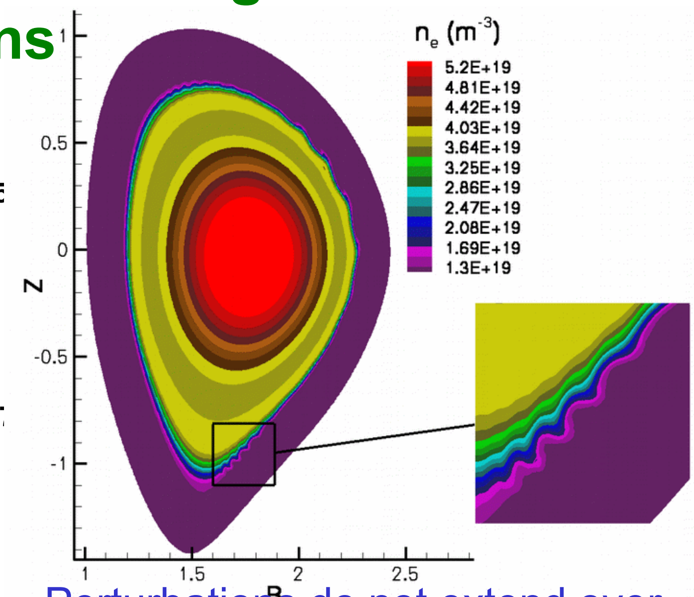


Two-fluid and single-fluid linear growth-rate spectrum for toroidal wavenumbers $0 \le n \le 42$ obtained with the 20×120 mesh of biquintic elements



Dissipation coefficients of $\chi_{||}$=1.5×10^7 m^2/s, $\chi_\perp$=1.5 m^2/s, and ν=25 m^2/s

Poloidal mesh of 20×120 with biquintic finite elements



Perturbations do not extend over entire outboard region like in single fluid simulations. Three groups of perturbations: one near separatrix, another on outboard side above midplane, and the third at the top of separatrix

Lessons Learned from Previous Studies

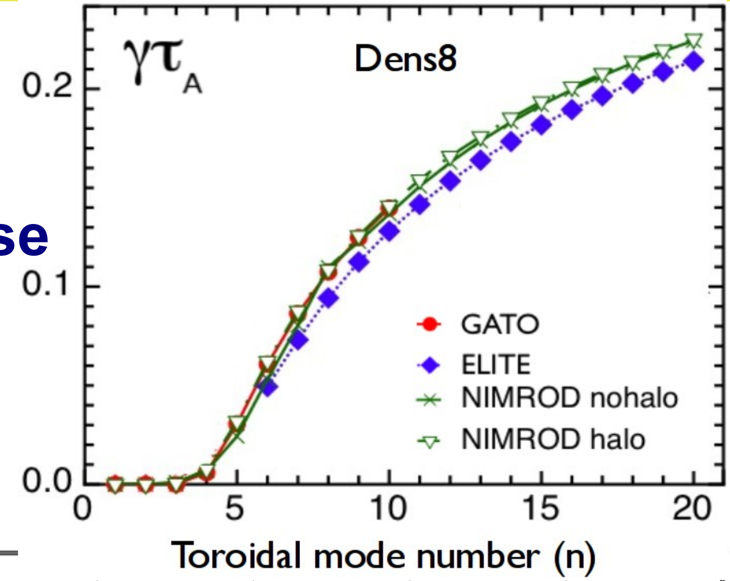
- Physics results strongly depend on the experimental profiles in the plasma edge region
  - This includes the pressure profiles in the pedestal and SOL regions
    - ELM is sensitive to both the resistivity (electron temperature) inside the LCFS (e.g. resistive destabilization) and the resistivity and density profiles outside LCFS (these profiles determine the degree of a vacuum-like response)
  - High quality measurement of plasma profiles are critical
- Resolution requirements with the two-fluid electric field and gyroviscosity are found to be very stringent
  - Convergence of ELM cases is challenging
    - Poloidal resolution
    - Solver issues

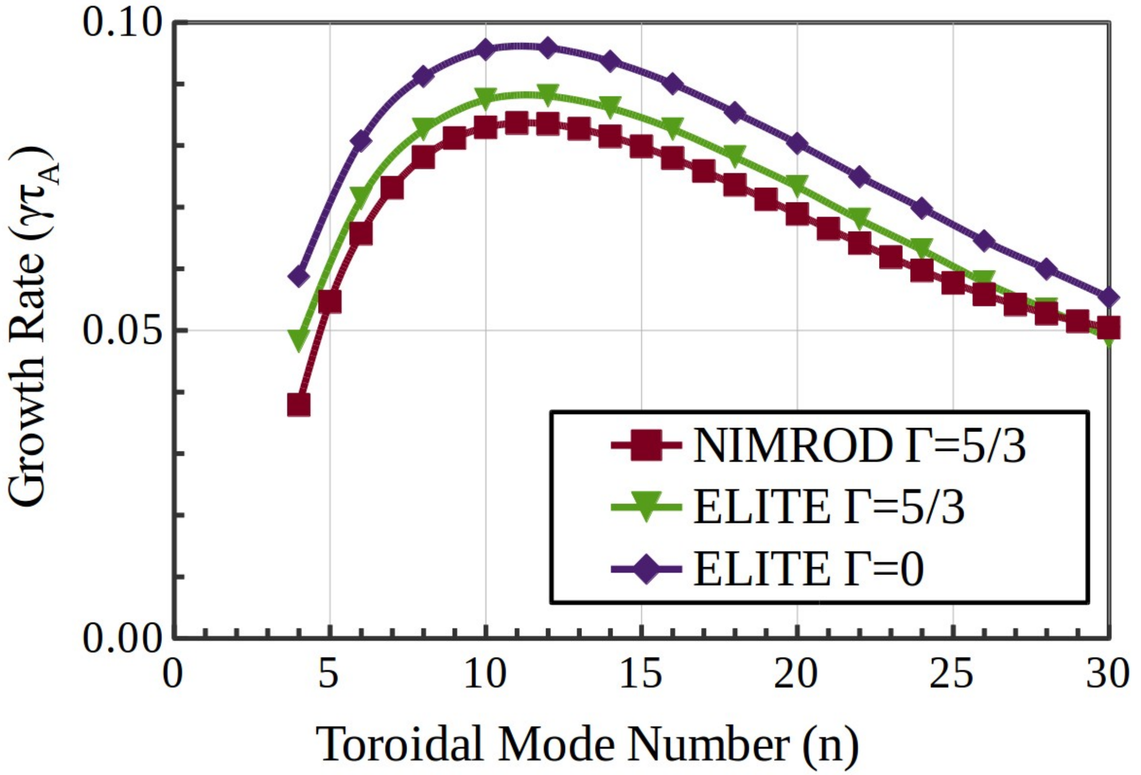
Current Capabilities in NIMROD Relevant to ELMs

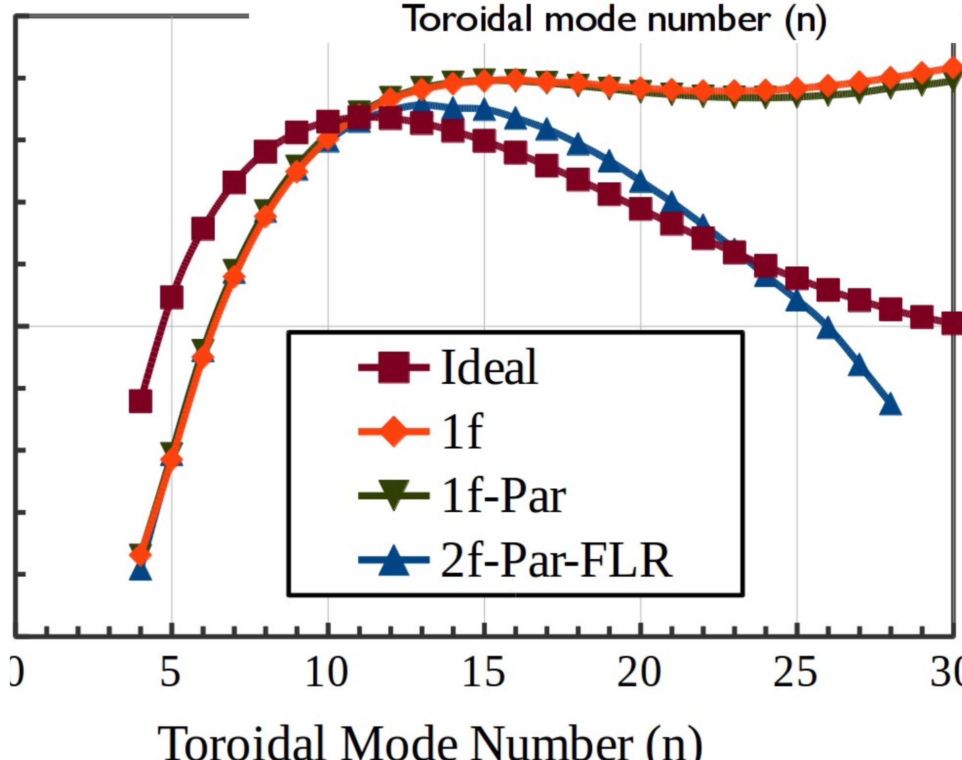
- **Physics basis [C.Sovinec JCP 2004]**
  - Complete Braginskii formulation is implemented
    - Hall term, gyroviscosity, ion parallel stress tensor [C.Sovinec JCP 2010]
    - Dissipation terms: resistivity, viscosity, thermal and particle diffusivities
  - Choice of closures: Braginskii, kinetic PIC [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**

Verification of NIMROD ELM Computations

- **The NIMROD, GATO, and ELITE code have been benchmarked [B. Burke PoP 2010]**
- **NIMROD results are compared with ELITE and M3D-C1 results for the MEUDAS benchmark case [N. Ferarro PoP 2010; J.King submitted to NF]**
  - **Based on JT-60U equilibrium**
  - **Resistive, two-fluid, and gyroviscous effects are compared**



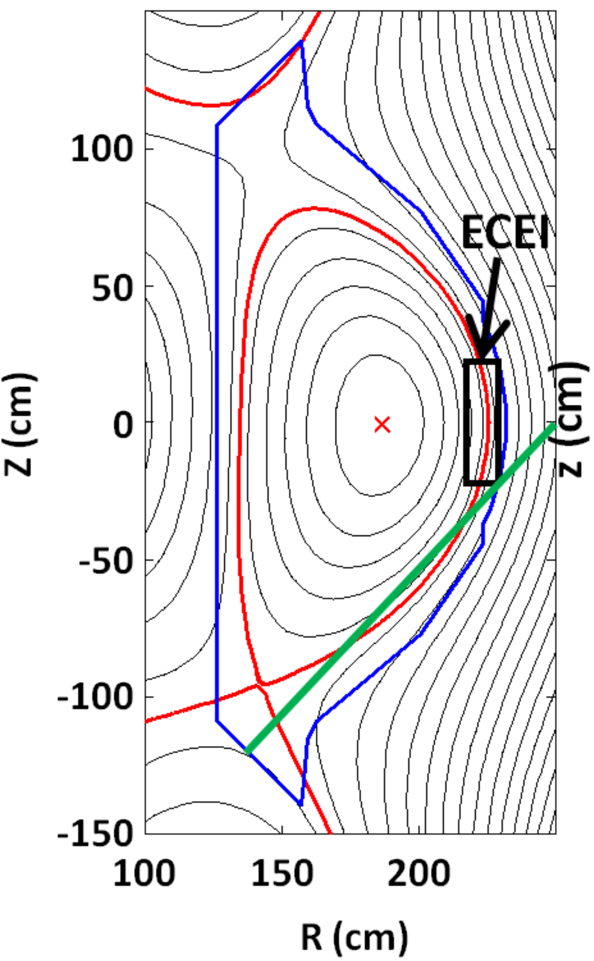




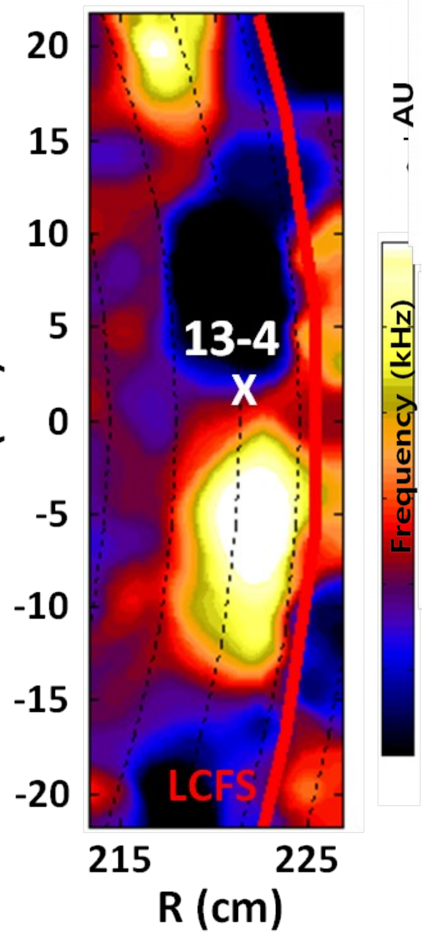
High resolution ECEI measurements in KSTAR can be used for understanding of ELM dynamics

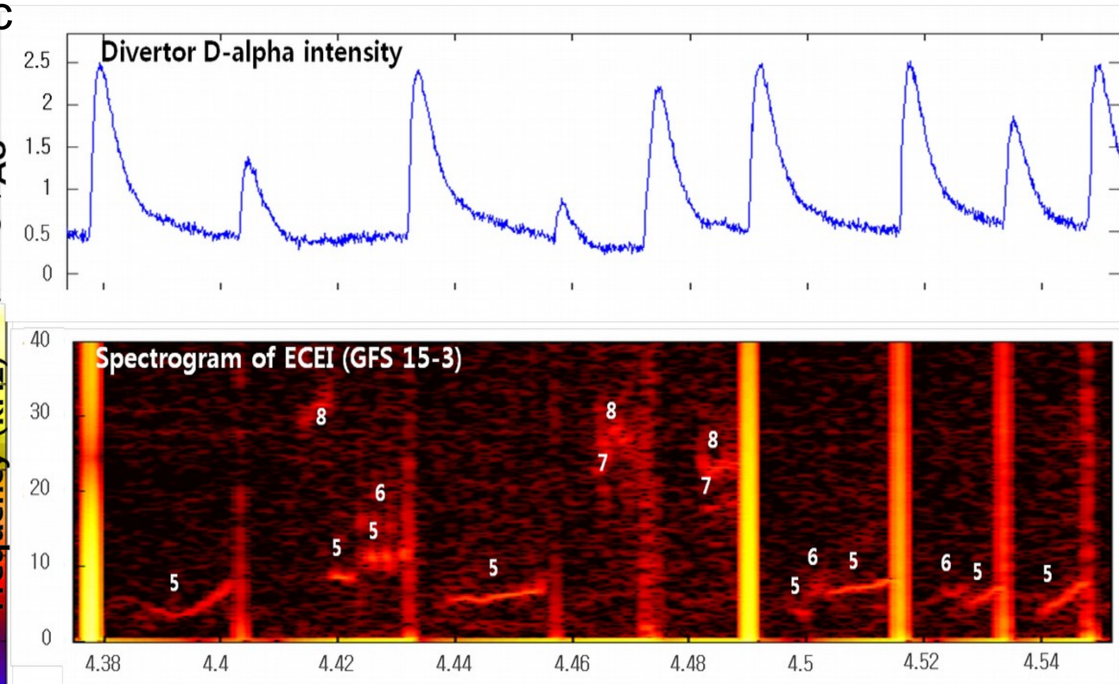
- **KSTAR discharge 7328: B_T=2.25 T, I_p=750kA, P_{NBI}=3MW, q_{95}=5**

EFIT at 4.36 sec



ECEI at 4.36 sec

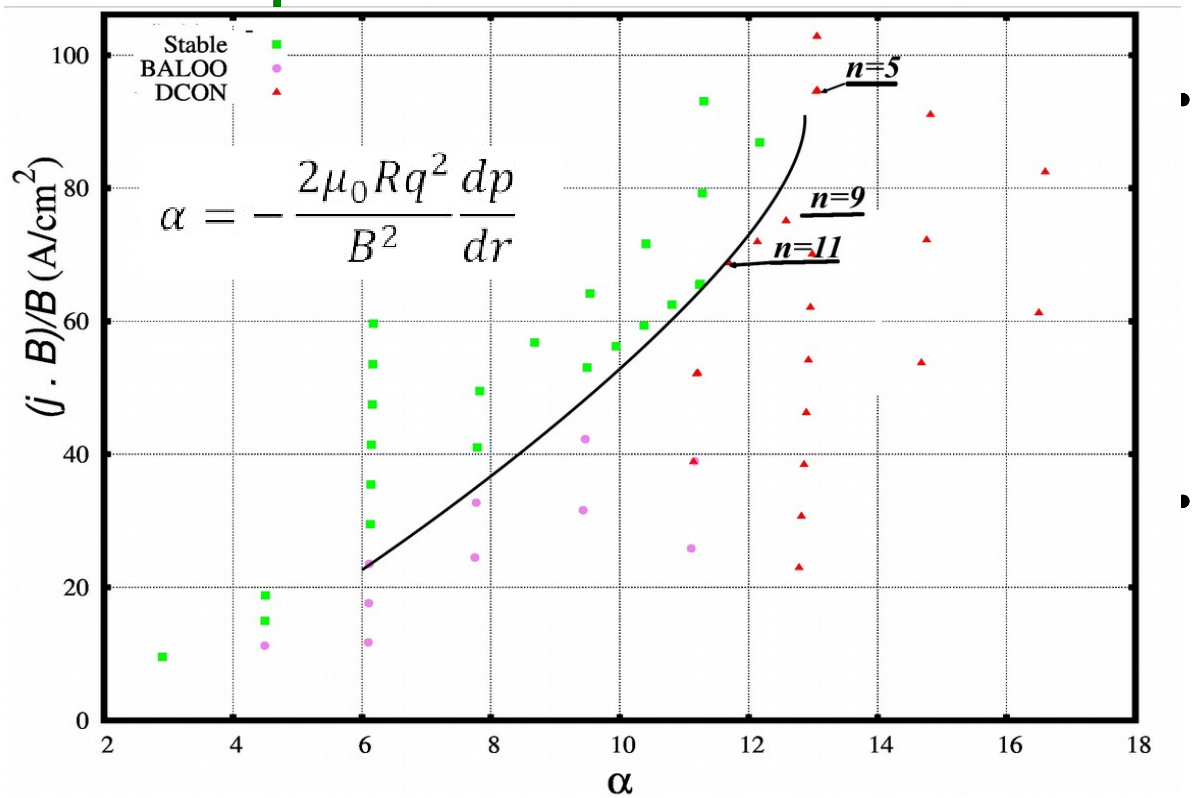




- **Very slowly growing modes are observed between large type I ELM crashes**
- **Mode number changes as pedestal builds up**
- **Typically, the toroidal mode number decreases with time**
- **During large ELM crash these modes disappear from the region of ECEI observation and reappear after ELM crash**

Interpretation of ELM observations

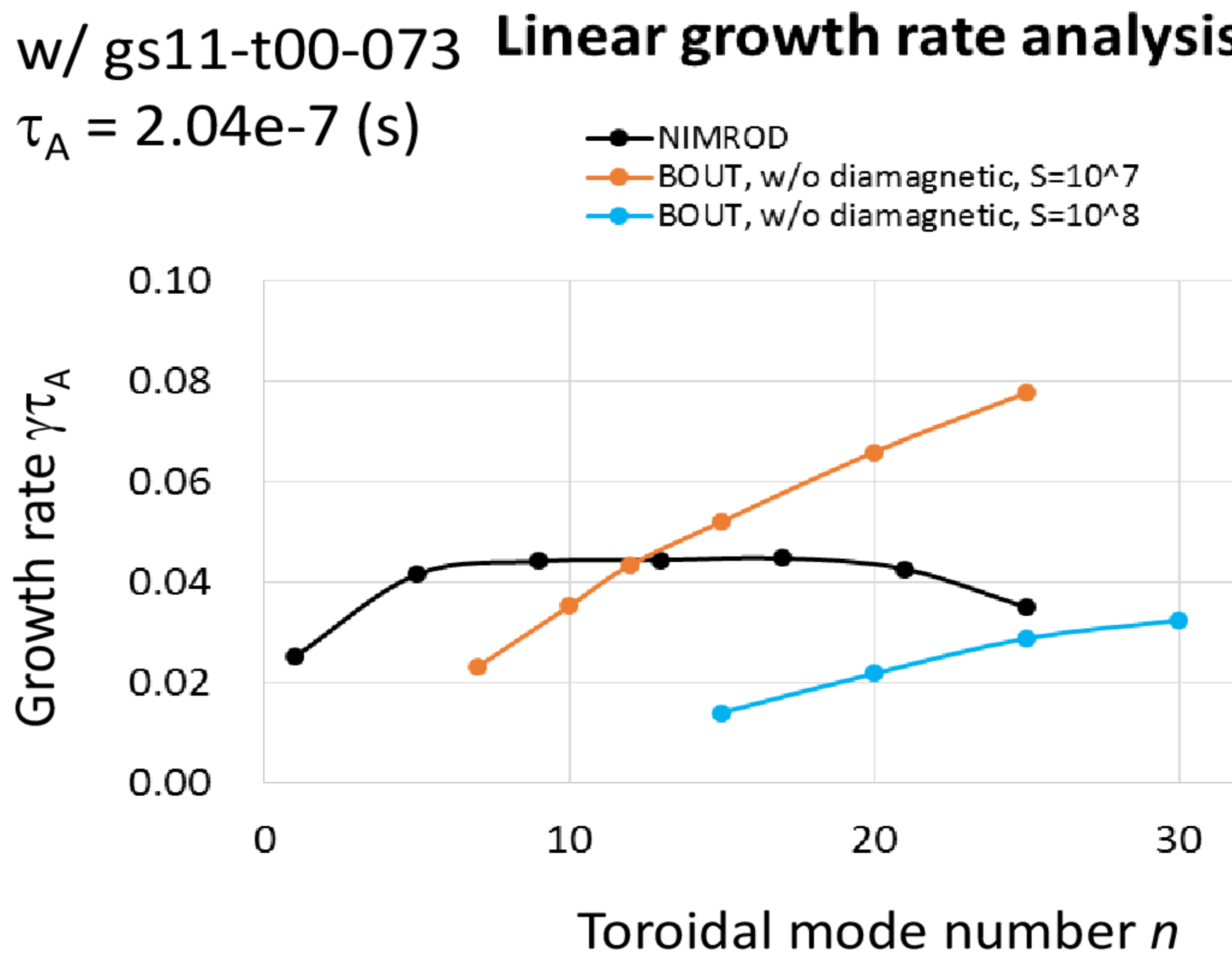
- **The modes observed in the KSTAR ECEI measurements are likely to be nonlinear saturated modes that might be related to triggering of ELM crashes**
  - **ELM crashes observed at KSTAR are typically triggered by n order of 12**
- **Linear stability analysis using ideal stability codes**
  - **n=5-11 modes are found in the range of experimental density and temperature measurements**



- **Ballooning stability boundary is shown. Parallel current densities that make the peeling modes unstable are found in the range of 135-150 A/cm^2, which is well outside experimental error bars**
- **n=5 and n=9 toroidal mode numbers that are close to the experimentally observed modes are marked on the diagram**

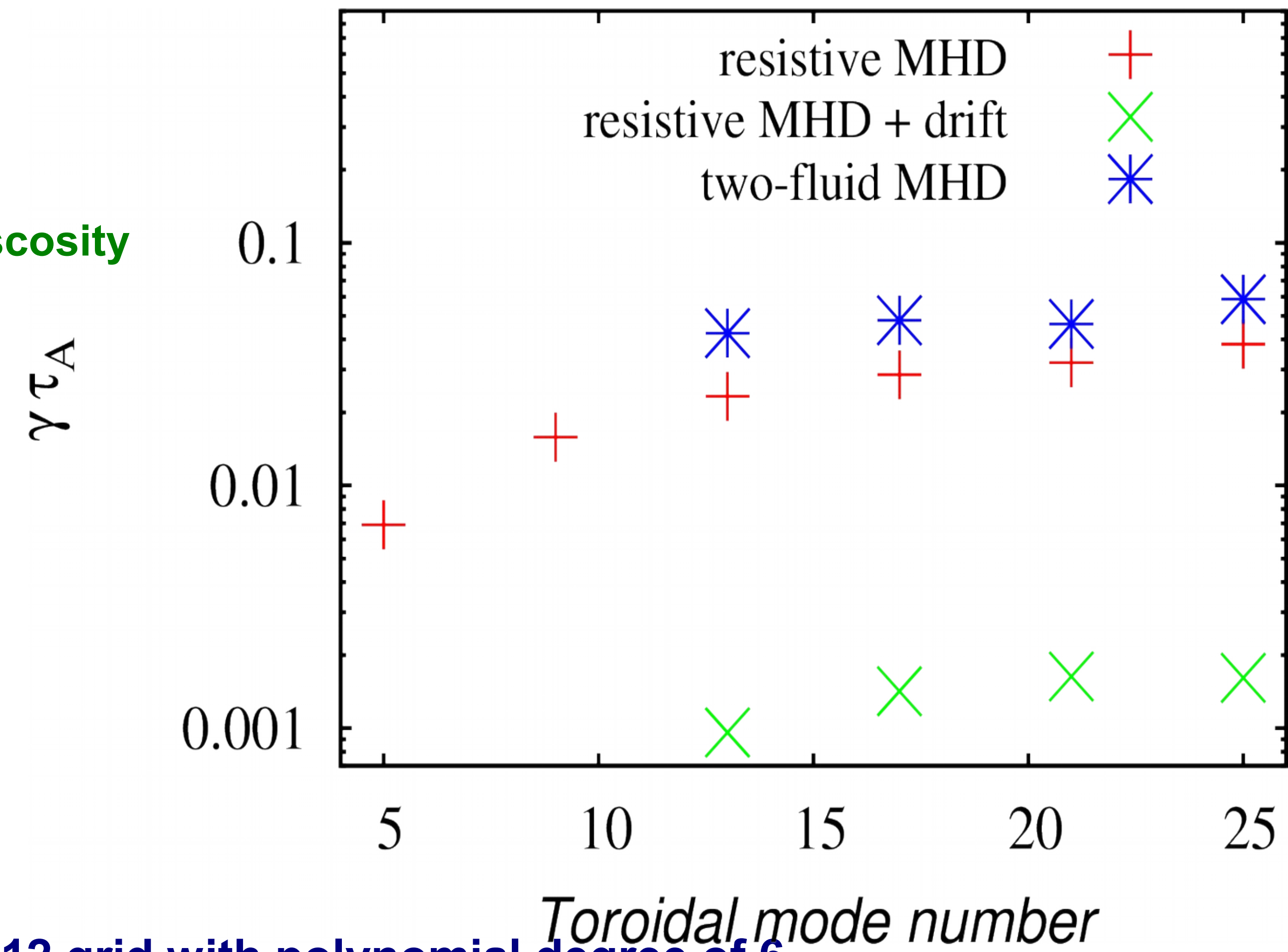
Verification of BOUT++ and NIMROD

- **Comparable resistivity in NIMROD and BOUT++ (*S*=10⁸)**
- **BOUT++ defines resistivity differently in this simulations**
- **Three-field model in BOUT++ does not evolve density separate from pressure**
- **Diamagnetic effects are included in BOUT++ and ignored in these NIMROD simulations**
- **Inclusion of drift effects in NIMROD result in a stronger than in BOUT++ mode stabilization**



Linear Extended MHD NIMROD Analysis

- **Equilibria generated for BOUT++ stability analysis are used in the NIMROD extended MHD studies**
- **Hierarchy of extended MHD models are considered**
- **Resistive MHD**
  - **Lundquist number S=10^8**
  - **Spitzer resistivity is used**
  - **No parallel viscosity or gyro-viscosity**
  - **No particle diffusivity, hyper-diffusivity or hyper-resistivity**
- **Resistive MHD with drifts**
  - **Parallel viscosity and gyro-viscosity are enabled**
  - **Particle diffusivity is enabled**
  - **No hyper-diffusivity**
- **Two-fluid MHD**
- **Two-fluid two-temperature MHD**
- **NIMROD simulations uses is 72x512 grid with polynomial degree of 6**



Linear Extended MHD NIMROD Analysis

- **In resistive MHD simulations**
  - All equilibria are found unstable with relatively weakly growing modes
  - Spectra shifted towards higher toroidal mode numbers comparing to BOUT++ analysis
- **Inclusion of gyro-viscosity and parallel viscosity result in significant stabilization of all modes**
  - Low n-modes are found completely stable
- **Adding two-fluid effects destabilize all modes**
  - Decoupling between electrons and ions is expected to be destabilizing
- **Two-fluid two-temperature MHD**
  - Modes with high n that might be related to ITG modes become unstable

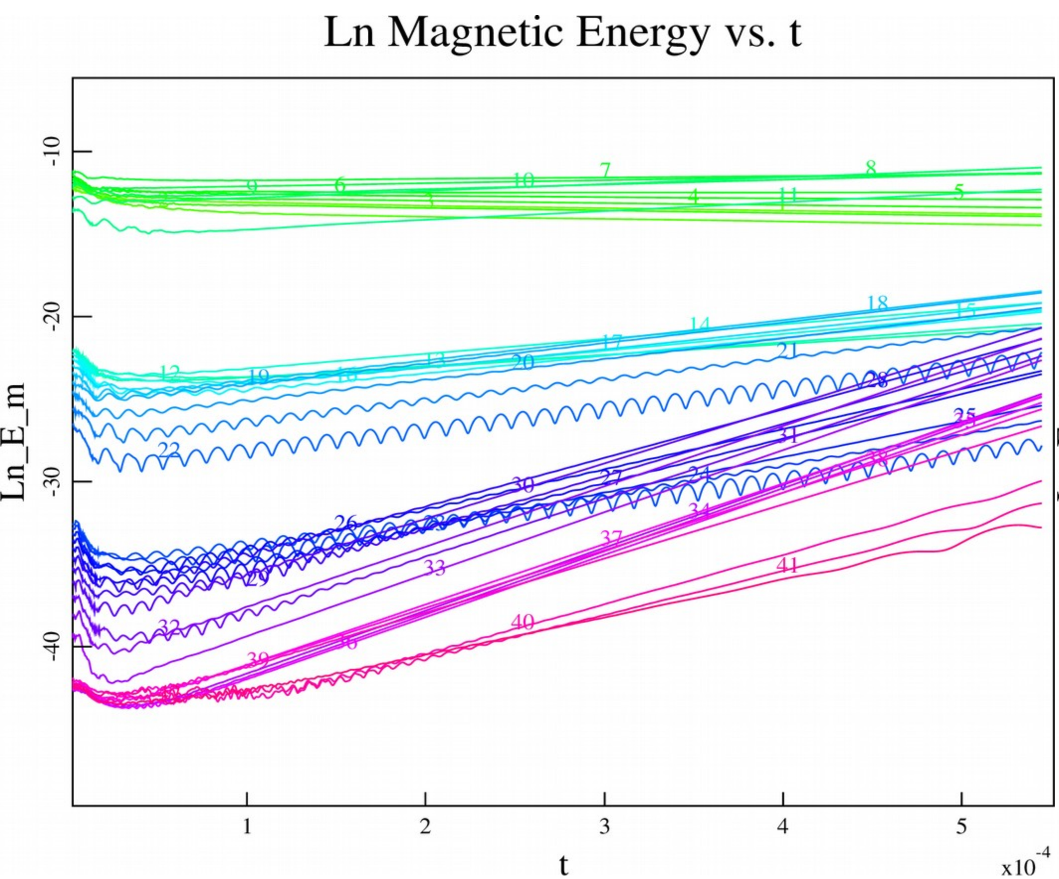
Nonlinear Simulation of KSTAR using NIMROD

- **Simulation utilizes high resolution grid**
  - 72x512 with pd=5 and 6 (compare 20x120 with pd=4 in ELM simulations ten years ago)
  - $S=10^8$ and Prandtl number of 0.1
  - No enhanced viscosity, perpendicular thermal diffusivity or particle diffusivity relative to Braginskii
  - Utilizes over 8,000 core on Edison
- **NIMROD has option to switch physics models during restart**
  - Simulation is started with 1fl model and continued with 2fl model

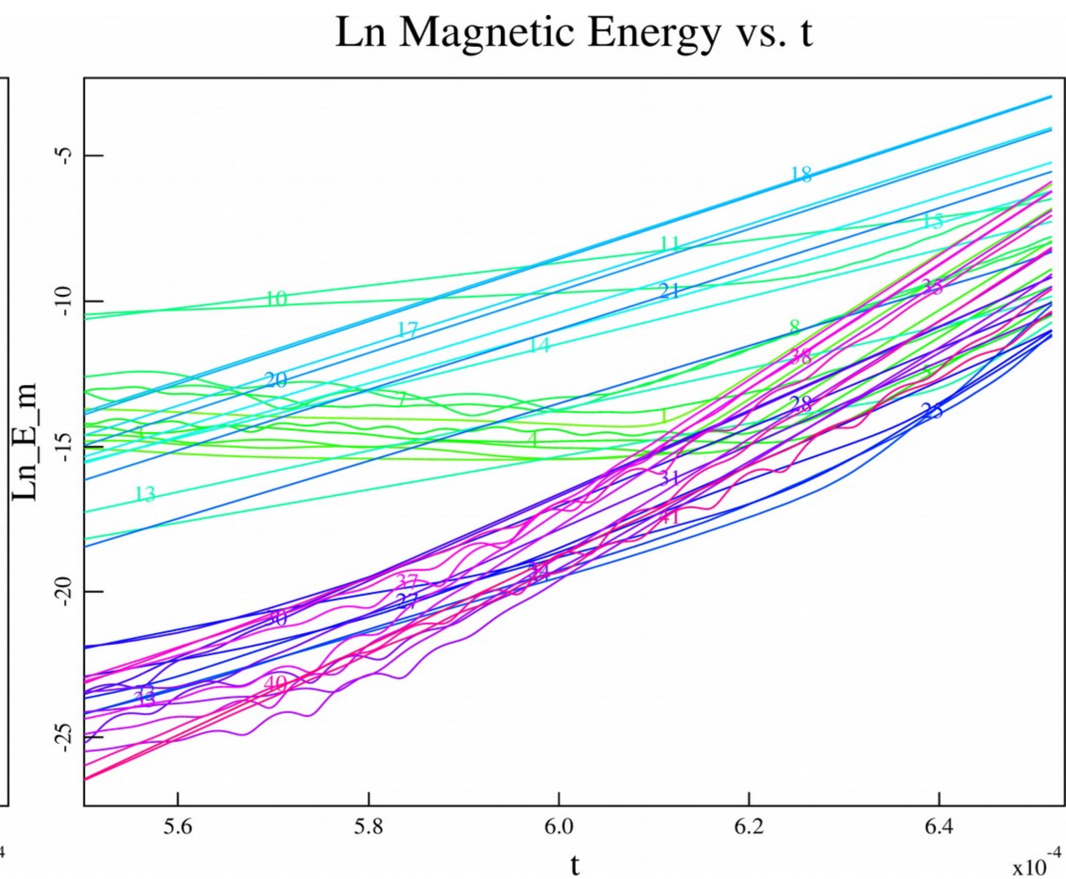
Nonlinear Simulation of KSTAR using NIMROD

Magnetic energy as function of time during linear and early non-linear stages

1fl

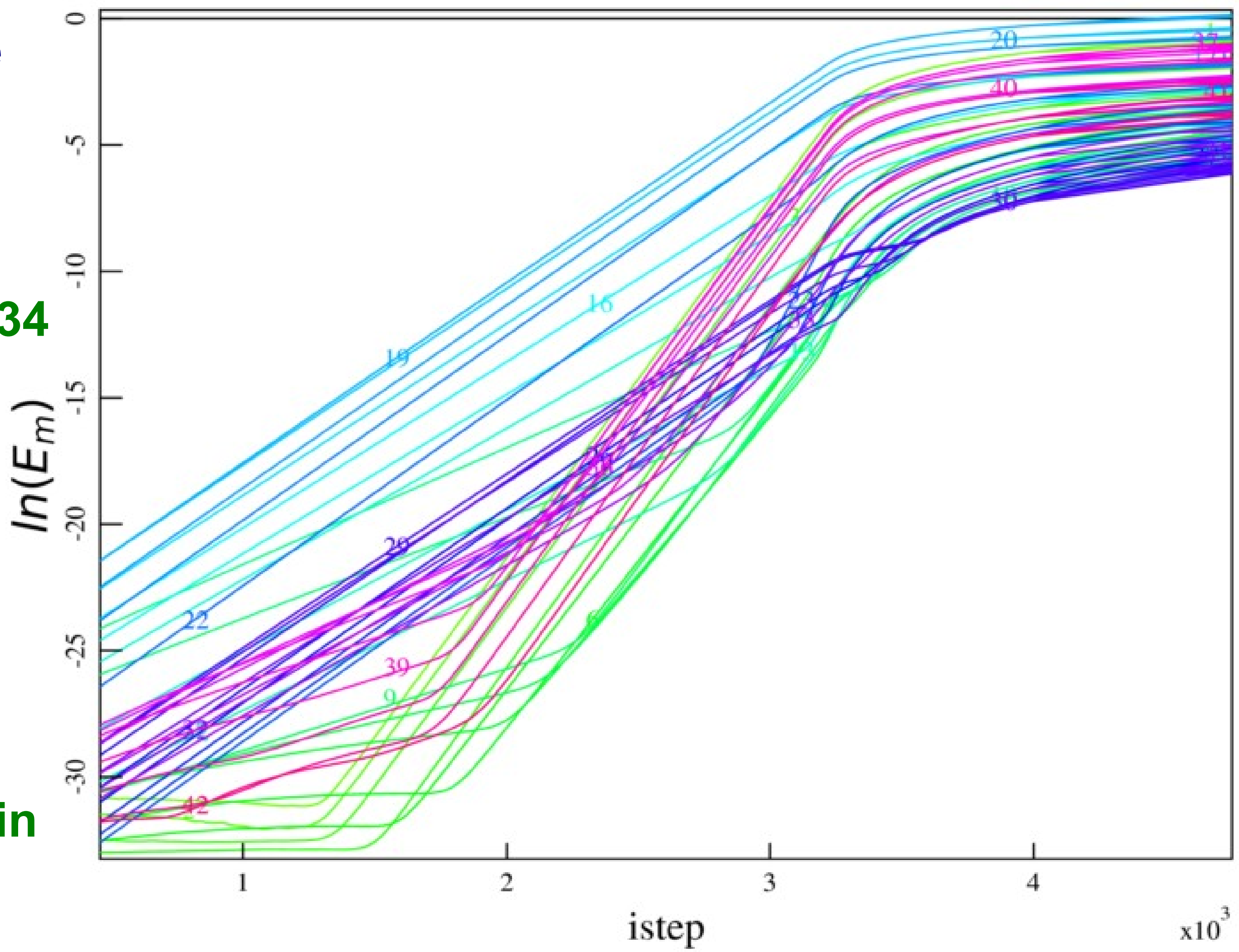


2fl



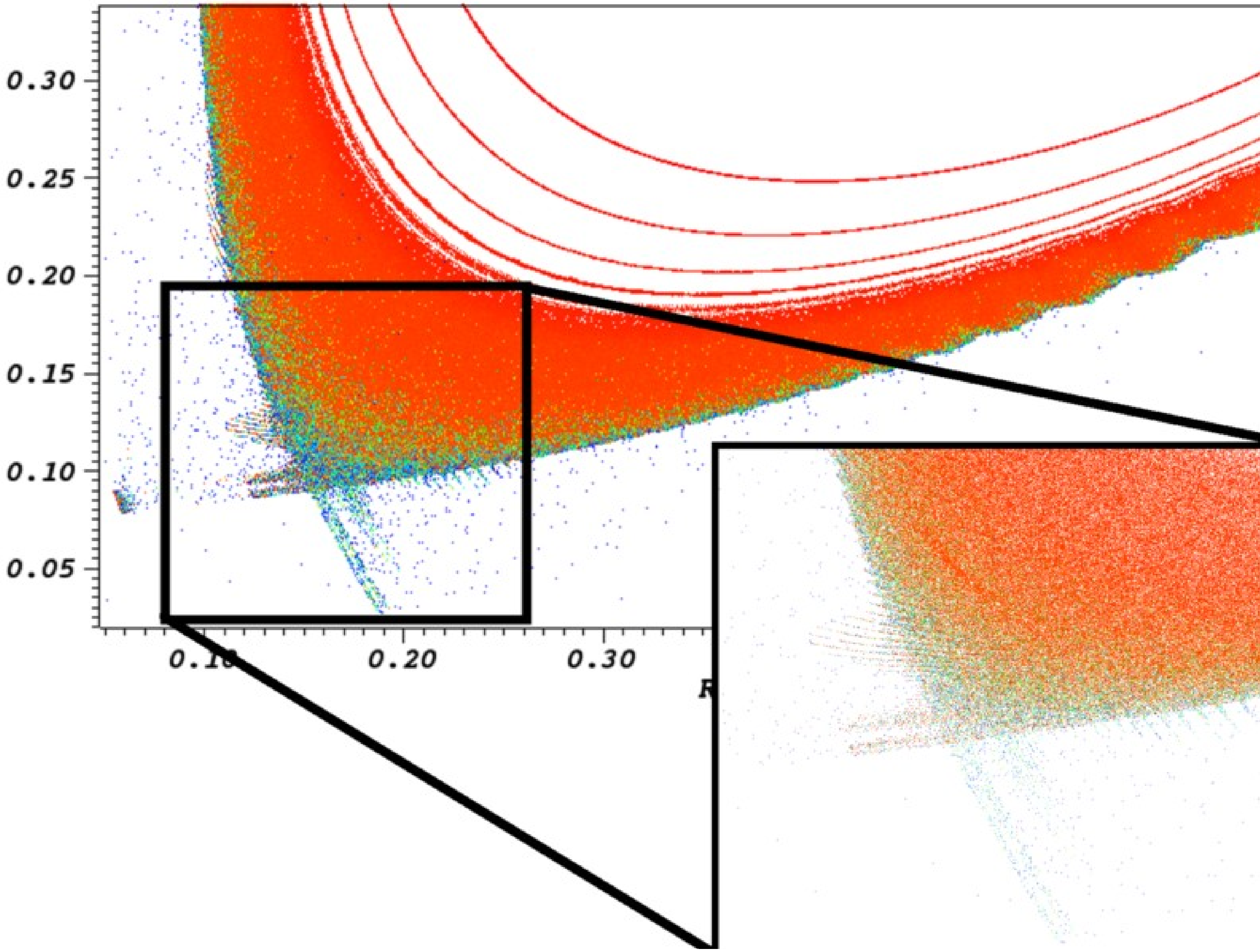
Nonlinear Simulation of KSTAR using NIMROD

- **ELM starts to saturate**
- **Dominant mode numbers are in the range from n=17 to n=21**
- **Direct cascade is found important**
  - **Modes in range from n=34 to n=42 are driven**
  - **It is important to include at least second harmonics in simulations**
  - **Results are found to be different comparing to M3D modeling of ELMs in DIII-D [L. Sugiyama Phys. Scr. 2012]**



Magnetic Tangle Developed

- **Magnetic perturbations become large enough and magnetic tangle developed**
  - Magnetic geometry of diverted X-point makes the plasma susceptible to reconnection
  - Hot plasma inside the LCFS can connect to the plasma facing components



Plasma Profiles in SOL are Important

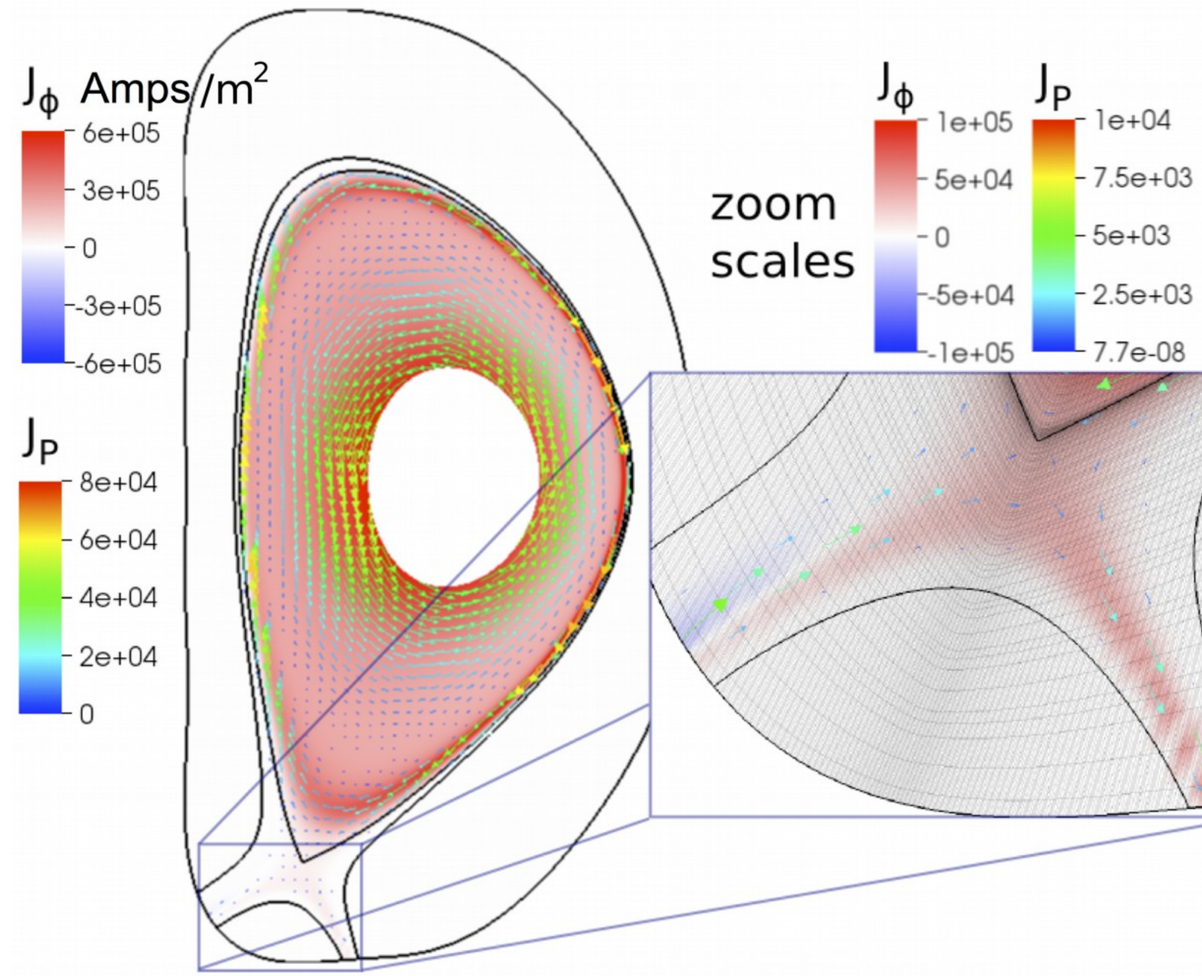
SOL profiles are important because

- These profiles allow realistic resistivity inside and outsIde LCFS
- SOL current profiles can help to 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



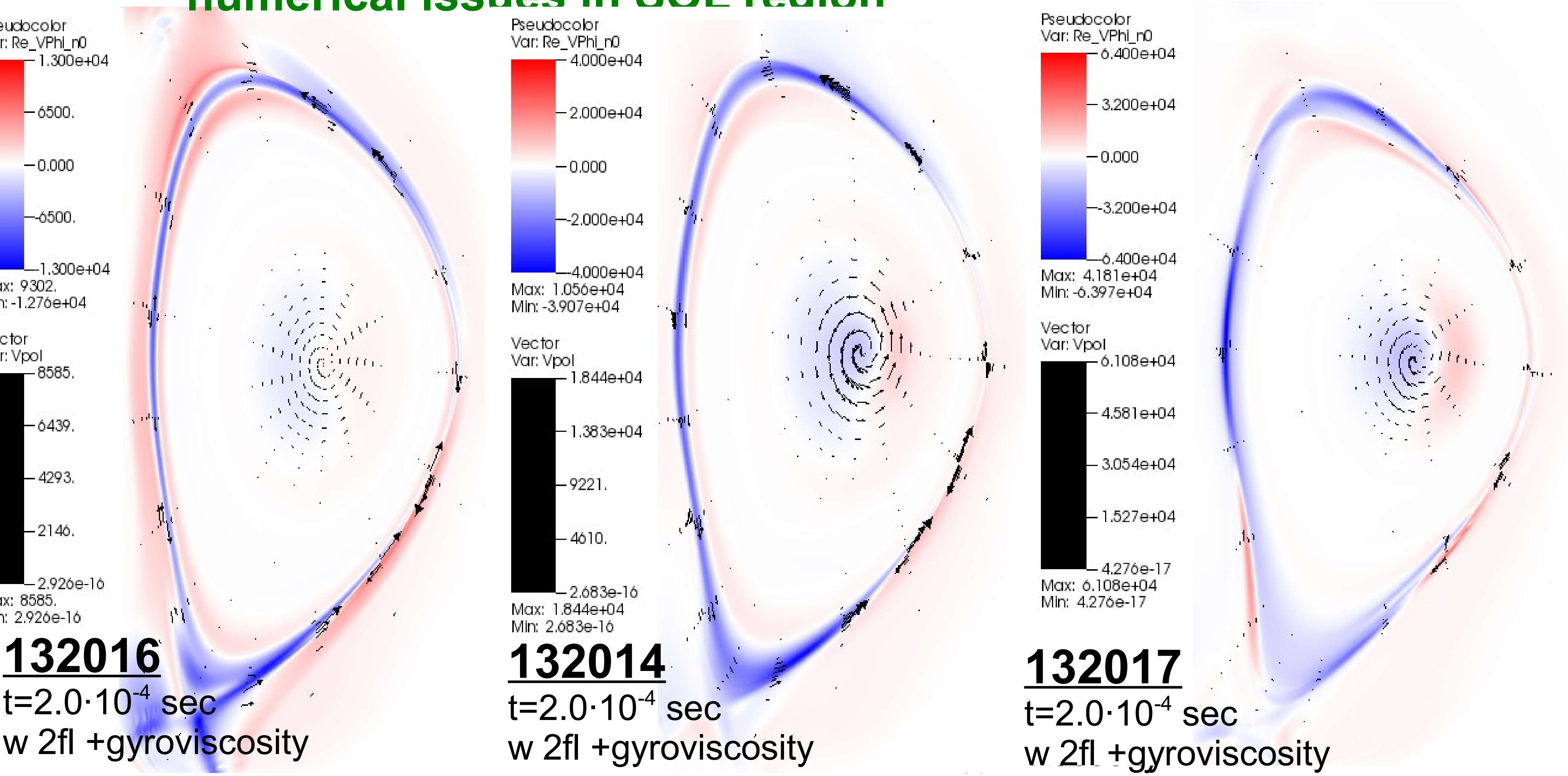
NIMROD for SOL Transport Studies

- **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**
  - **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 DKE-closures for axisymetric transport modeling**
  - **NUBEAM and TORIC in TRANSP and ONETWO for sources**
- **Multiple ELM cycles can simulated in NIMROD**

Flow Comparison for Discharges with Different Plasma Currents

Two-fluid and FLR effect increase these differences between poloidal and toroidal flows

– Use of local and global upwinding schemes helps to resolve numerical issues in SOL region



132016
$t=2.0\cdot10^{-4}$ sec
w 2fl +gyroviscosity

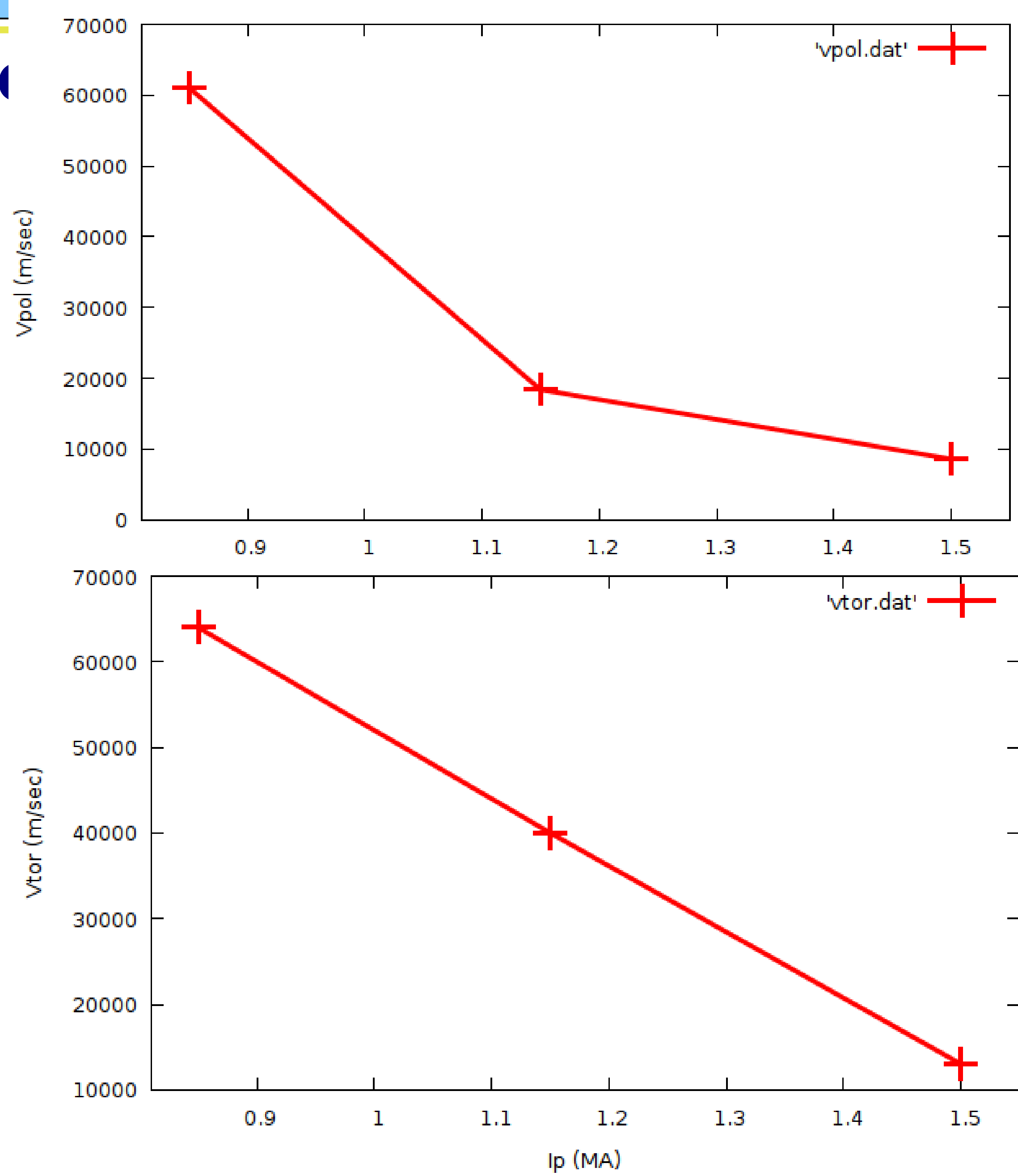
132014
$t=2.0\cdot10^{-4}$ sec
w 2fl +gyroviscosity

132017
$t=2.0\cdot10^{-4}$ sec
w 2fl +gyroviscosity

Flow Comparison for Discharges with Different Plasma Currents

Toroidal and poloidal vel are smaller in the discharges with larger plasma currents

- Effect is likely related to different resistivity profiles
- Discharges with larger plasma currents have larger temperatures in H-mode pedestal region
- Neoclassical effects are not included in these simulations yet



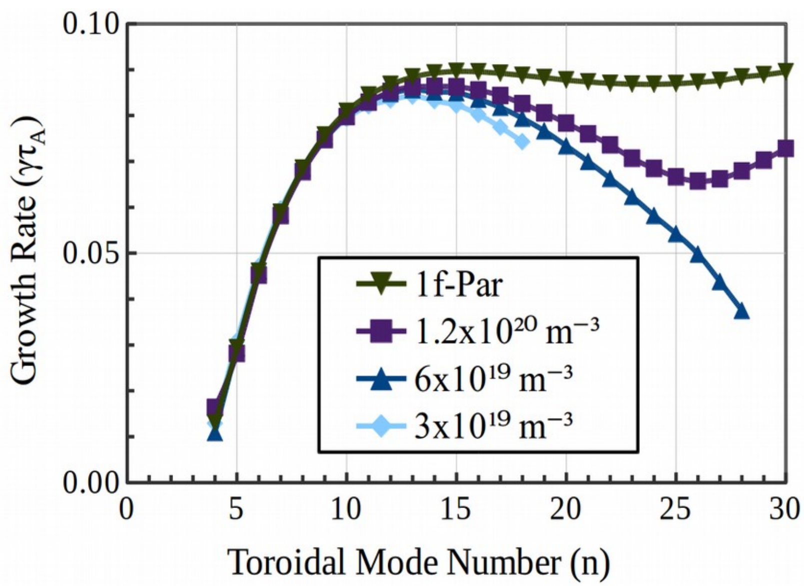
Summary

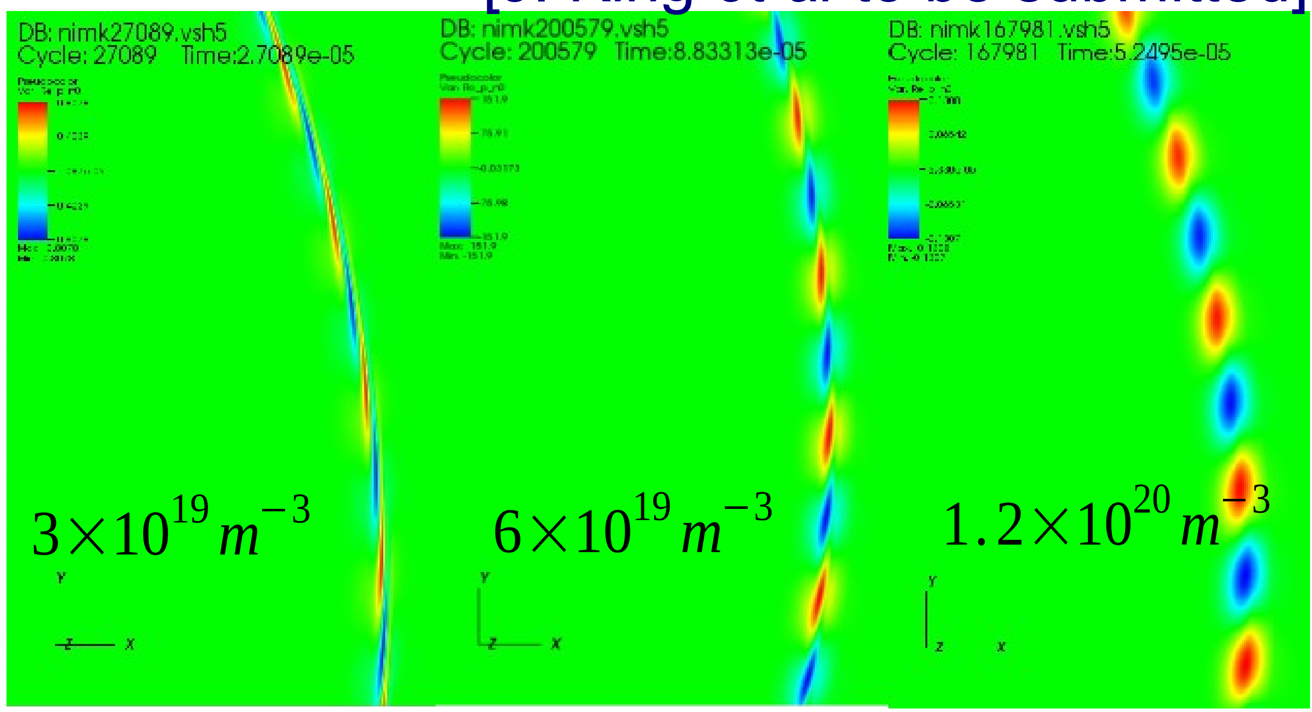
- NIMROD capabilities for ELM modeling are presented
  - FGNIMEQ tool for resolve Grad-Shafranov equilibria on NIMROD grid
  - Plasma profiles and plasma currents are extended to SOL
  - MEUDAS benchmark case is extended to study collisionality effects
    - Most unstable mode numbers shifted towards lower n for cases with higher temperatures due to FLR effects
    - High-n mode stabilized due to FLR effects
  - Equilibrium evolved in extended MHD code result in large SOL flows
    - Resistivity gradient is found to have little effect on SOL flows
    - 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
    - SOL flows decrease with the plasma current
    - SOL flows can significantly change the ELM dynamics
  - New closures are being developed and tested
- KSTAR ELM modeling results are presented
  - Two-fluid MHD is important for linear and nonlinear dynamics
  - Direct cascade is found important
  - Magnetic tangle developed

MEUDAS Benchmark is Extended to Study Collisionality Effects

- **Equilibrium is not changed**
  - This includes the pressure profiles and bootstrap current
  - Density and temperature profiles are scaled up and down
  - FLR effects are expected to be larges for the case with smaller density and larger temperature
- **Most unstable mode numbers shifted towards lower *n* for cases with higher temperatures**
- **High-*n* mode stabilized due to FLR effects**

[J. King *et al* to be submitted]





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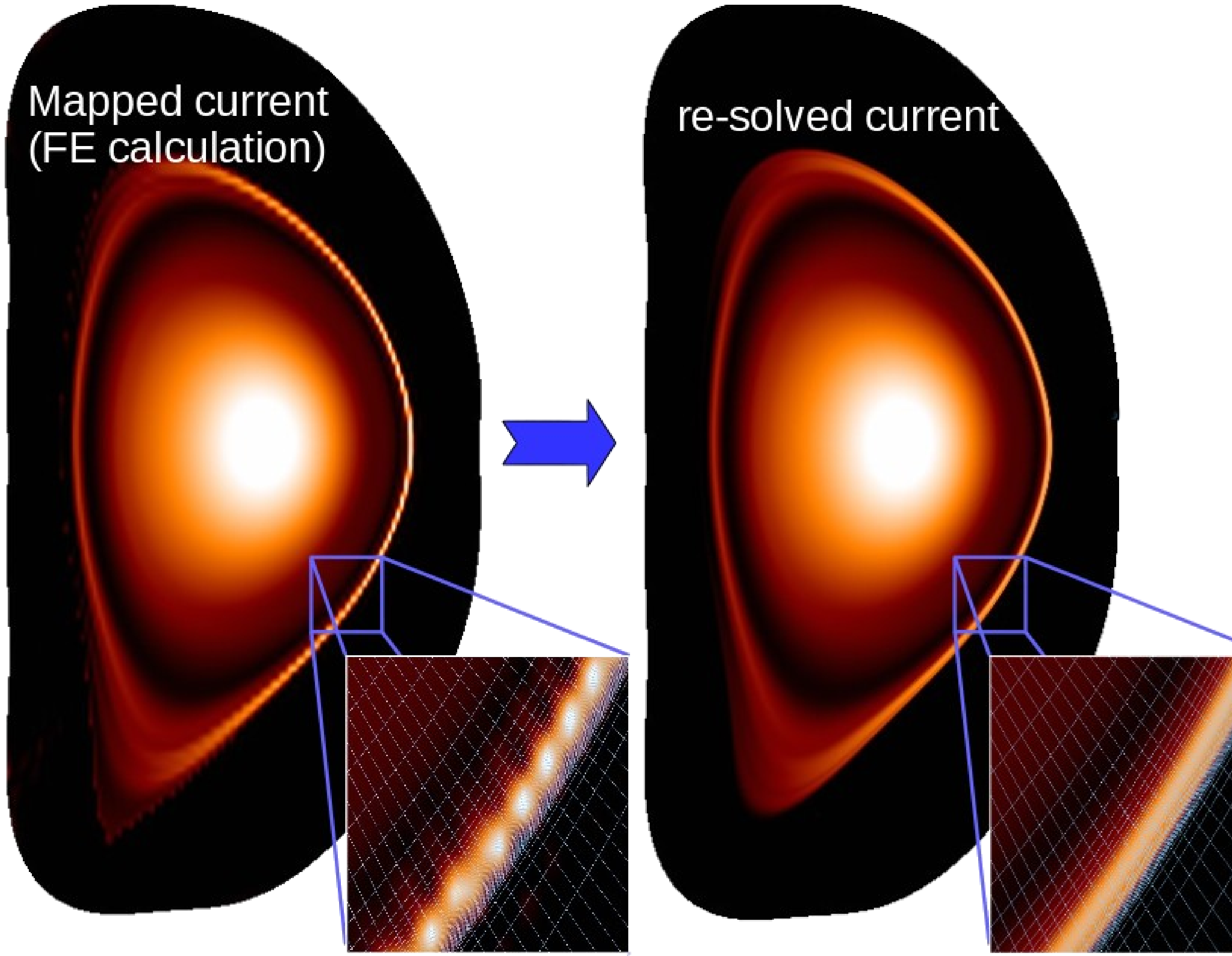
FGNIMEQ Development

- **Mapping issues between experimental equilibria and NIMROD grid are addressed**
  - Developed from NIMEQ solver [Howell CPC 2014] and FLUXGRID equilibrium mapper
  - Allow using low resolution experimental equilibrium reconstruction in NIMROD for edge problems



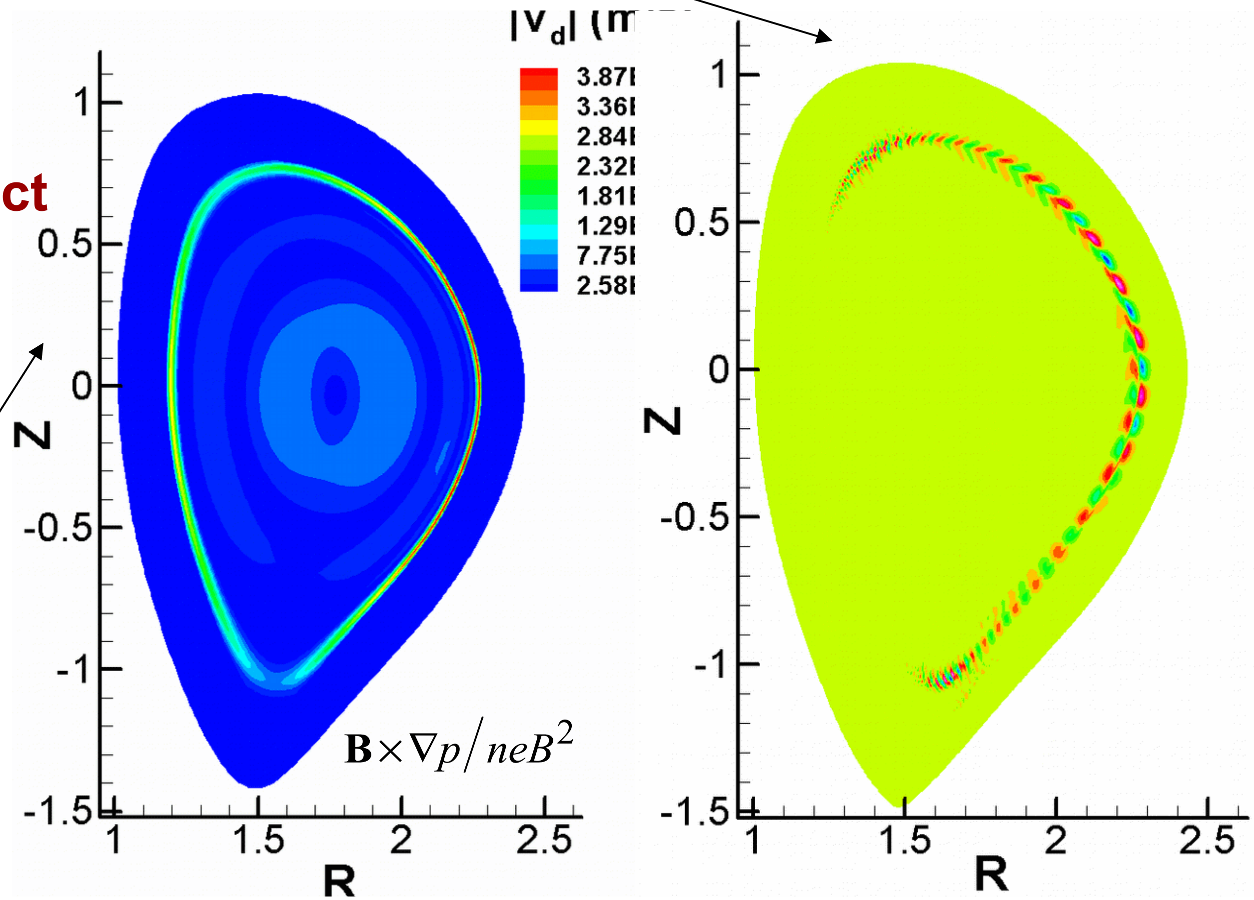
Two-fluid and FLR Effects

- **Analytical estimate of diamagnetic stabilization [K. V. Roberts and J. B. Taylor, PRL 8 (1962)] suggests stability at** $\omega_{*i} \equiv mv/r = 2\,\gamma_{MHD}$

Observed $\gamma_{MHD} \cong 2\times10^5$, $r \cong 0.5$ m, $q \cong 3$

- **Than, one might expect stability at n=m/q of order unity**

The radial extent of the diamagnetic drift is narrower than ELM eigenfunctions, and radial localization is known to reduce the stabilizing effect of ion diamagnetic drift [R. J. Hastie, *et al* PoP **7** (2000)]



Poloidal component of diamagnetic drift velocity and toroidal component of flow velocity for the n=21 eigenfunction computed with two-fluid model