Modeling of ELM Cycle Using XGC0 and NIMROD in CPES Framework

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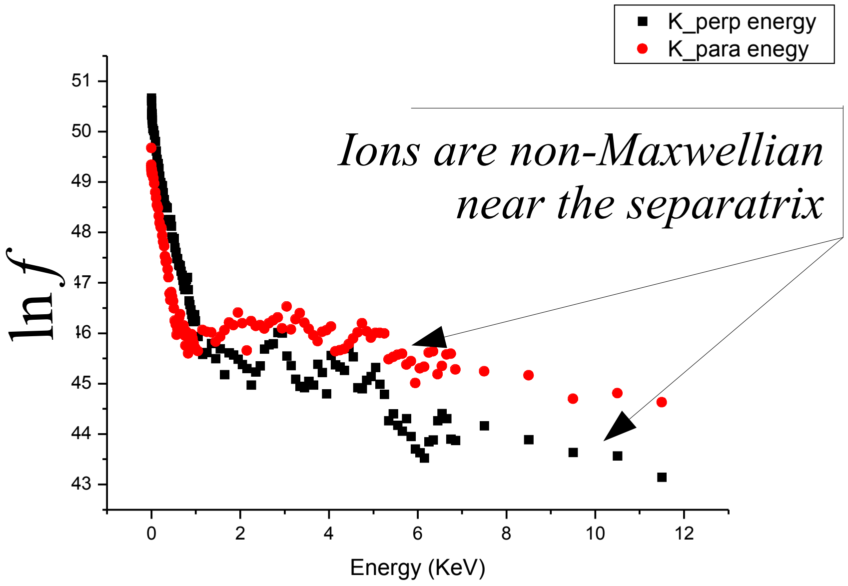
Outline

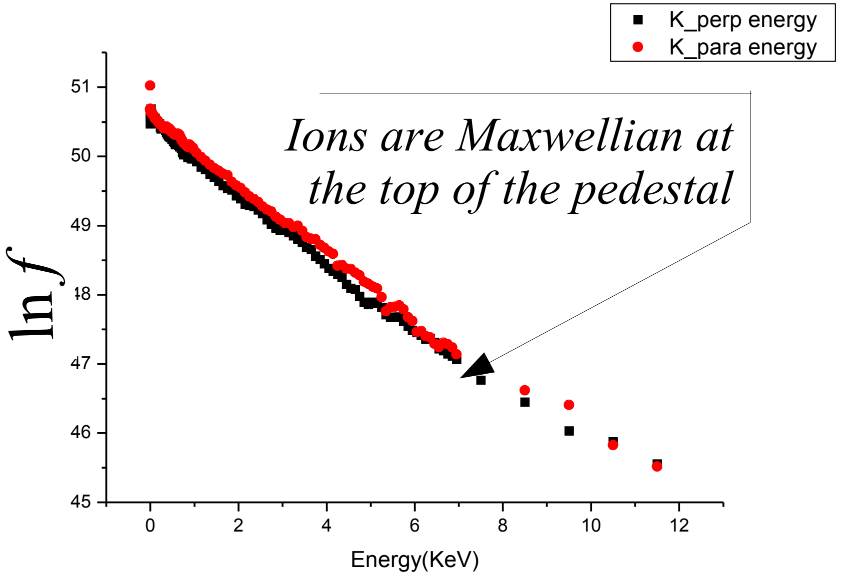
- Edge Physics in Tokamaks
- Center for Plasma Edge Simulations (CPES) Framework
  - Kinetic XGC0 code
  - Ideal MHD stability ELITE code
  - Extended MHD NIMROD code
- Simulation results of ELM crash for DIII-D discharge
- Discussion

Edge Physics in Tokamaks

- **Requires time dependent, integrated understanding of**
  - Edge kinetic neoclassical physics
  - Edge kinetic turbulence physics
  - Core turbulence
  - MHD physics
    - Large scale edge localized modes (ELMs)
  - Neutral, impurity and atomic physics
  - Scrape-off-layer physics
  - Wall load, neutral recycling, and sputtering
  - Energetic particle influx from core
  - RF interaction of edge plasma
  - 3D magnetic field effects



Ions are non-Maxwellian near the separatrix



Ions are Maxwellian at the top of the pedestal

Kinetic Code for Tokamak Edge Simulation

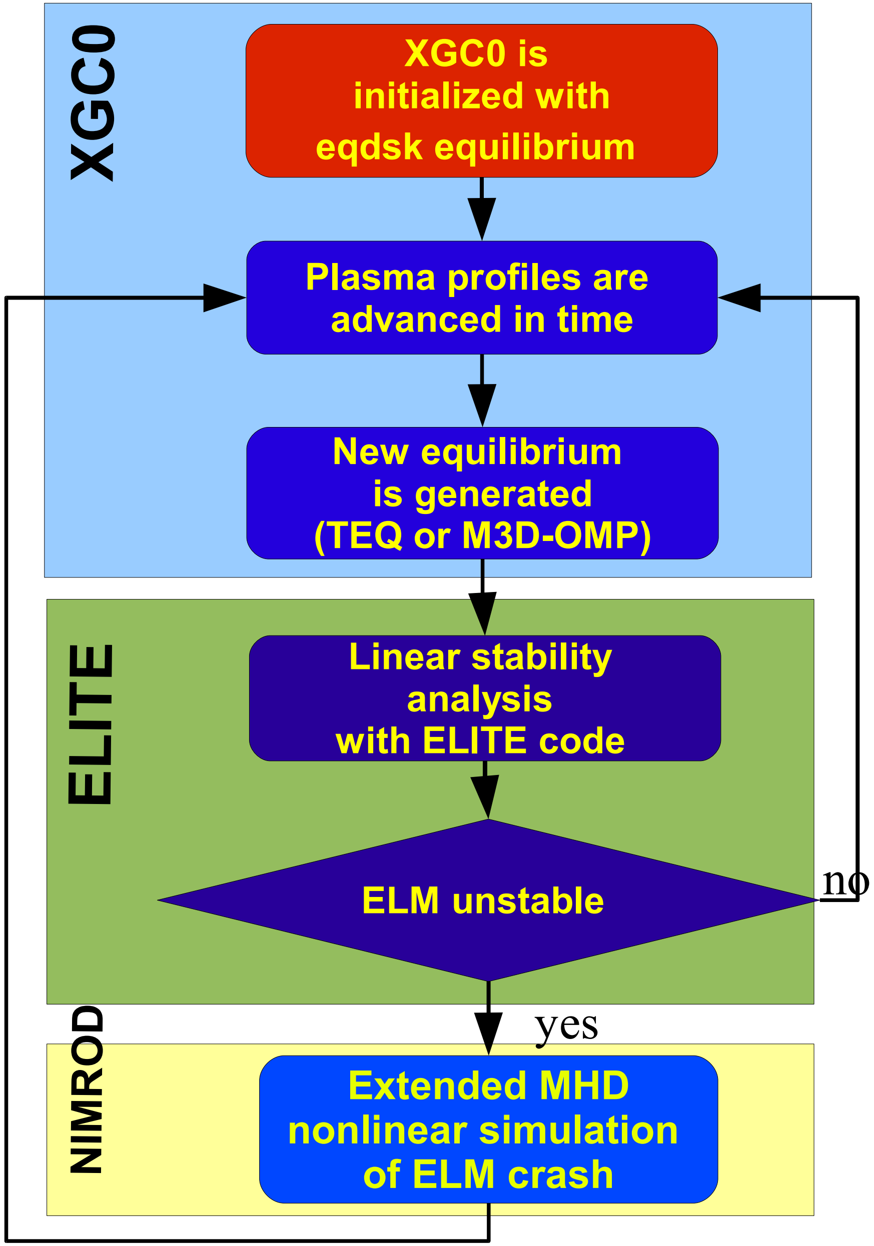
- Challenges for Edge Kinetic Modeling
  - Special treatment for open field lines and divertor geometry is required
  - Steep gradient and X-transport generate strong neoclassical E-field and highly non-maxwellian distribution functions
  - Neutral collision and ionization plays an important role in the H-mode pedestal build up
- XGC : X-point included Gyrokinetic Code
  - Full-f particle code for ions and electrons including neutral collisions
  - XGC0 : Guiding Center code. Average-out turbulent E-field
  - XGC1 : Electro-static gyrokinetic code

CPES Computational Framework

Coupled XGC0-ELITE-NIMROD simulation of H-mode pedestal formation and ELM cycle dynamics

Kinetic XGC0 code

- **Follows 5D guiding center dynamics**
- **Is much faster than most kinetic codes**
  - 1D solution for electric field: axisymmetric component of E_r
- **Ion/electron/neutral, full-f**
- **Conserves collisions**
- **Evaluates kinetic bootstrap current, and the corresponding Grad-Shafranov equilibrium**



CPES Computational Framework

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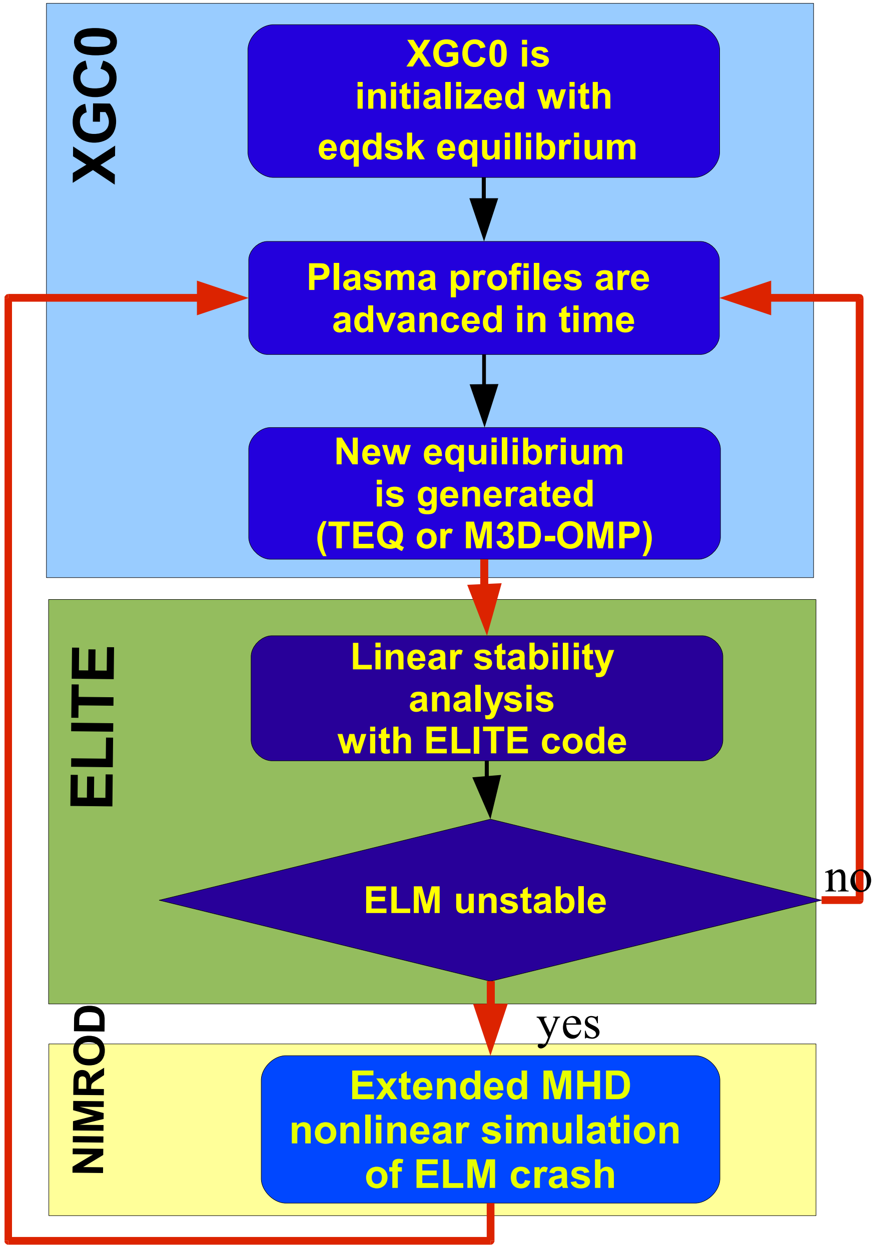

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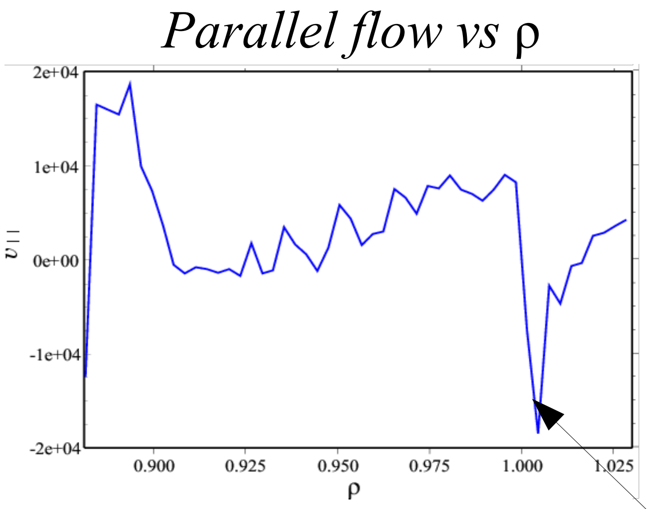
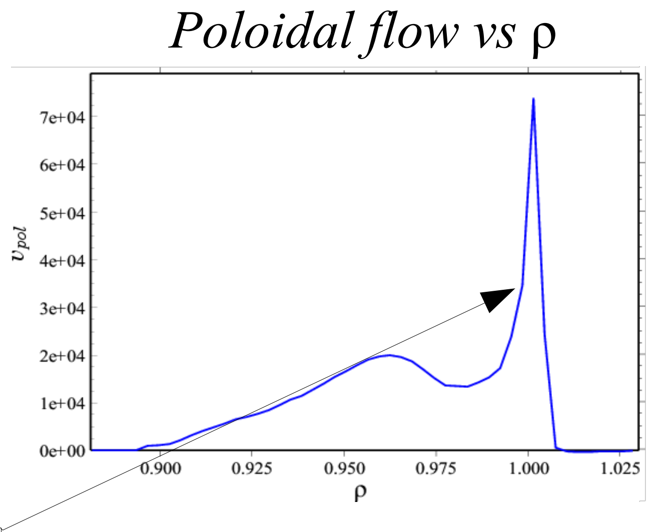
Coupled with other codes (ELITE, M3D, NIMROD) through the Kepler integration framework

XGC0 Modeling of H-mode Pedestal Buildup

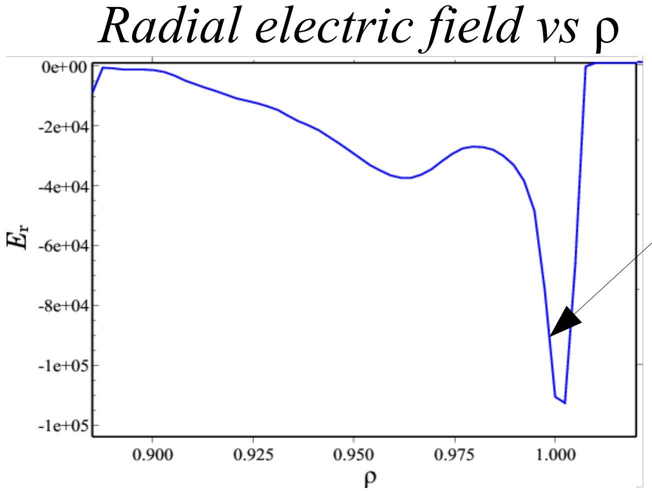


Parallel flow vs ρ



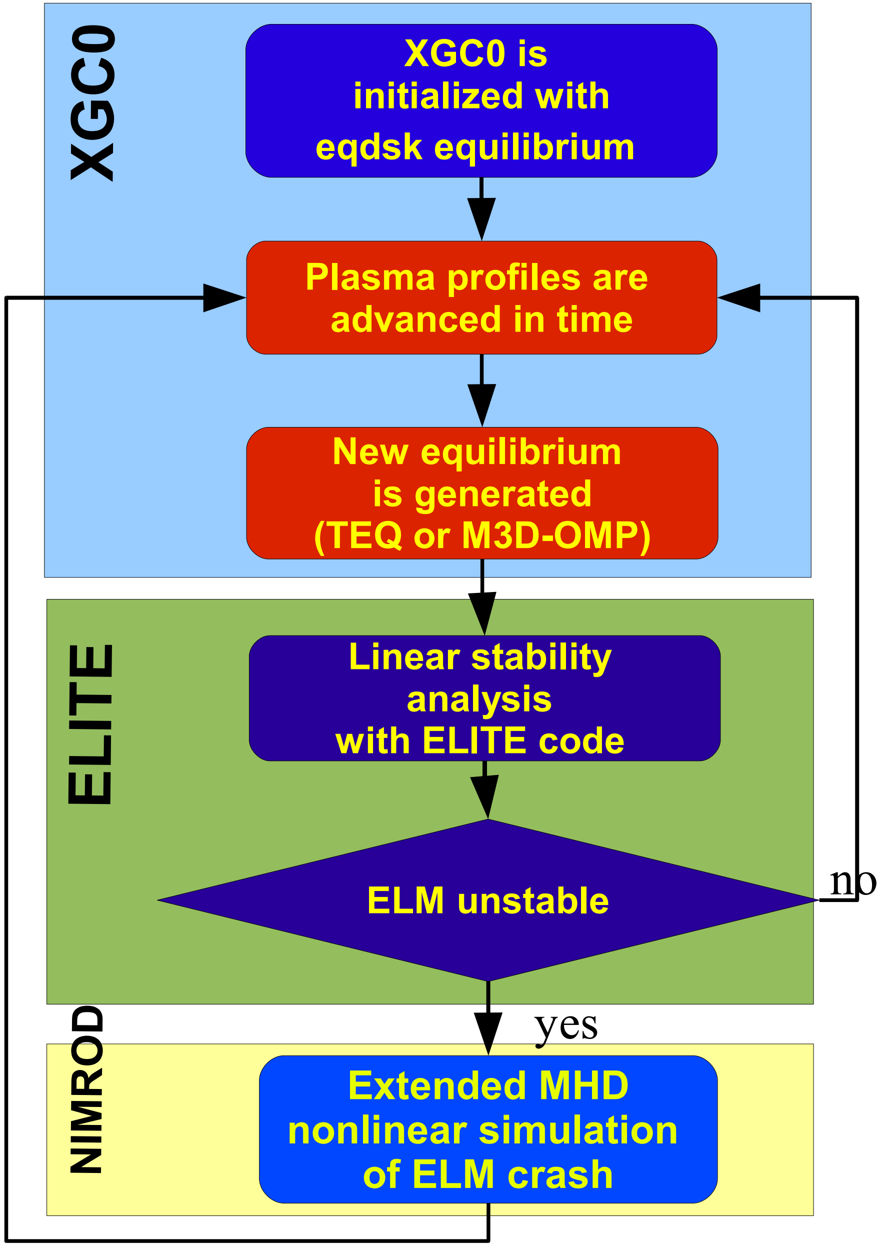
Poloidal flow vs ρ

Parallel and poloidal flows as functions of minor radius demonstrate the redistribution of fluxes near the separatrix



Radial electric field vs ρ

Formation of shear radial electric field and ***E*x*B*** flow shear in the H-mode pedestal region is qualitatively consistent with experimental observations in terms of direction and localization



XGC0

XGC0 is initialized with eqdsk equilibrium

Plasma profiles are advanced in time

New equilibrium is generated (TEQ or M3D-OMP)

ELITE

Linear stability analysis with ELITE code

ELM unstable

no

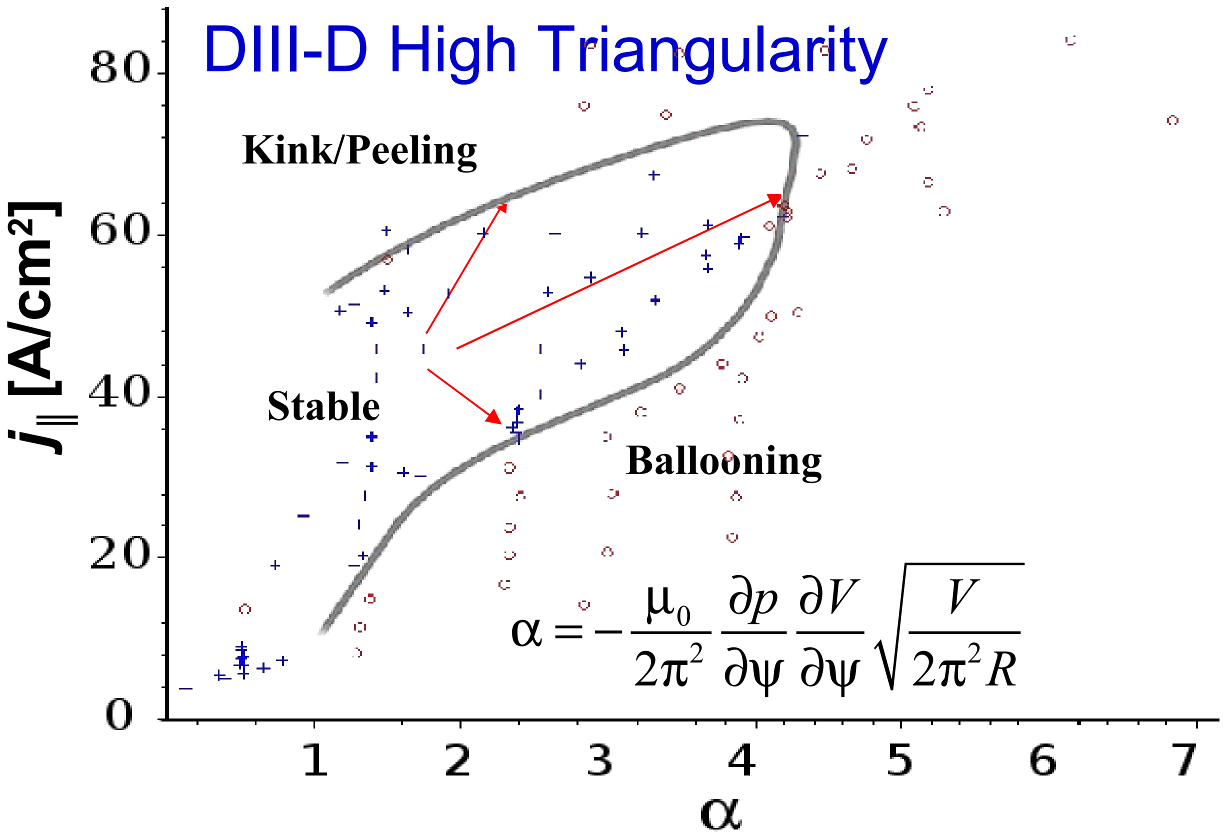
yes

NIMROD

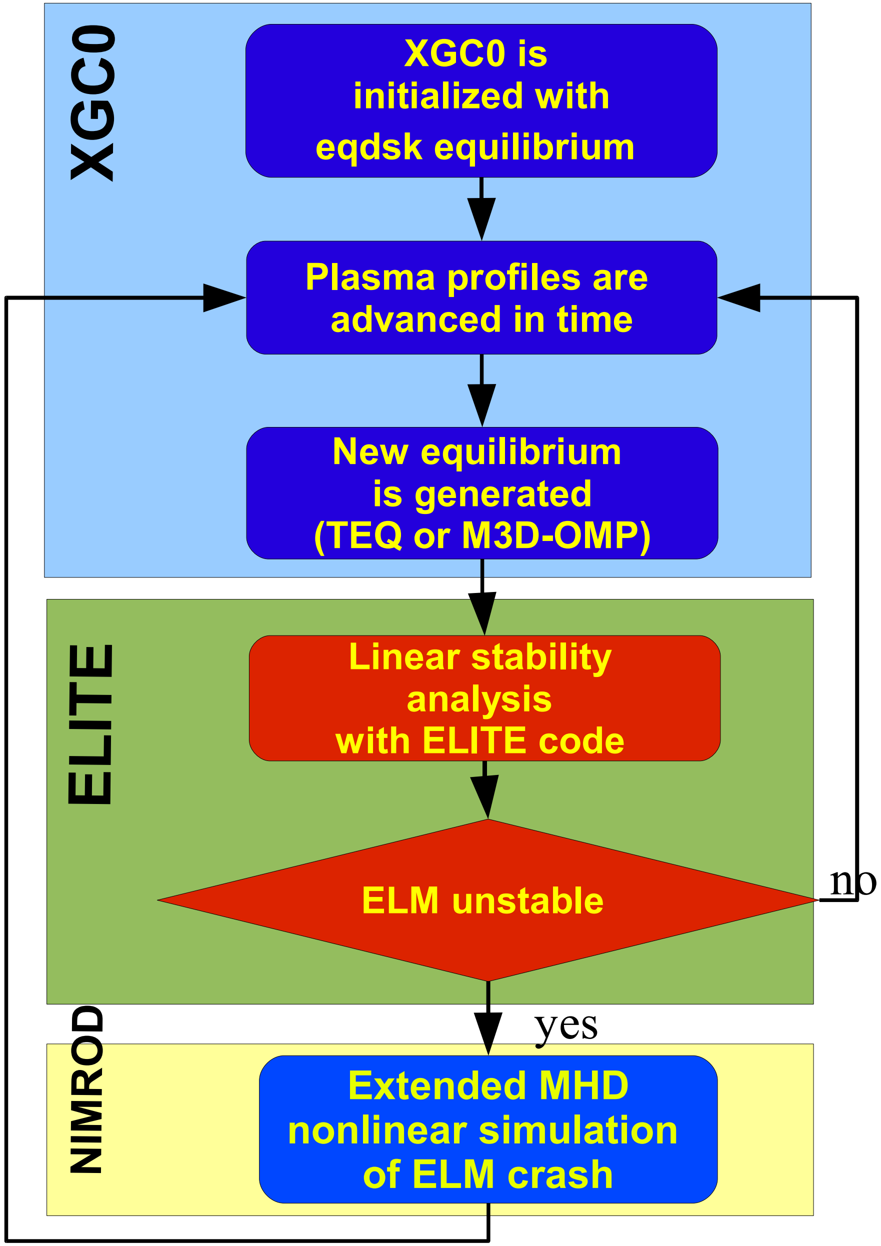
Extended MHD nonlinear simulation of ELM crash

Stability Analysis with ELITE Code

- **ELITE code (developed by P. Snyder and H. Wilson):**
  - Computes intermediate to high n (> 5) ideal MHD instabilities
  - Uses extension of the ballooning formalism through two orders in 1/n
  - Determined peeling-ballooning stability boundaries



$$\alpha = -\frac{\mu_0}{2\pi^2}\frac{\partial p}{\partial \psi}\frac{\partial V}{\partial \psi}\sqrt{\frac{V}{2\pi^2 R}}$$



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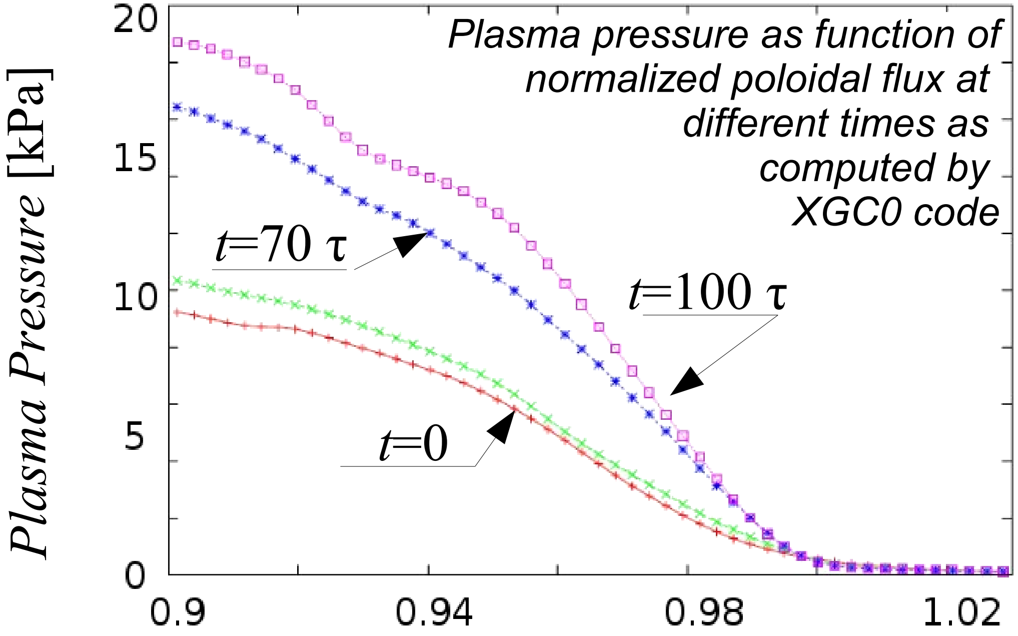

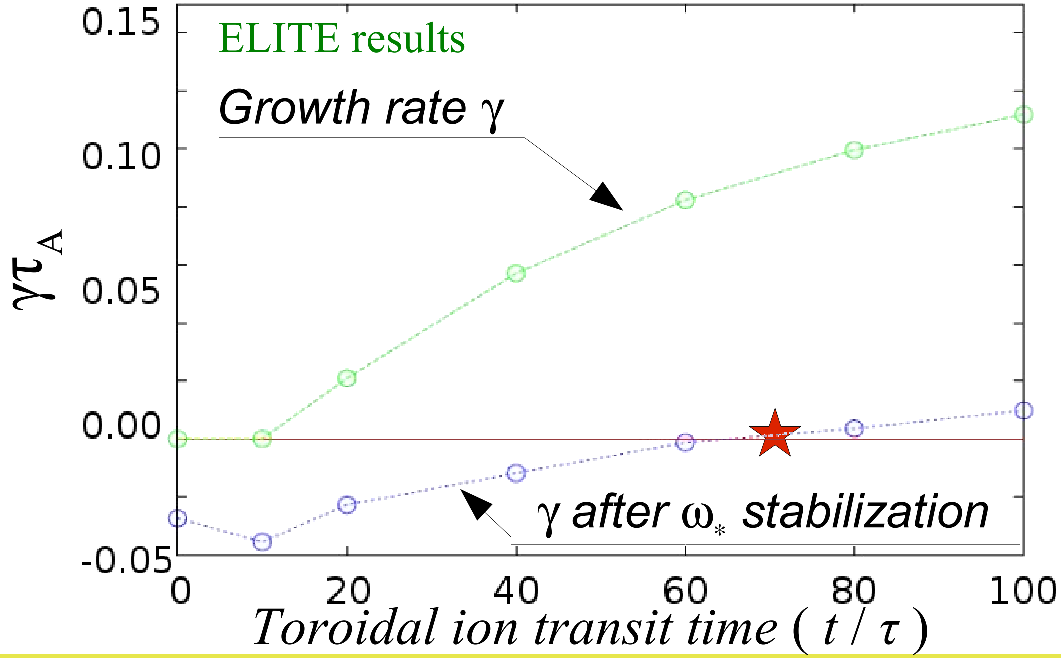

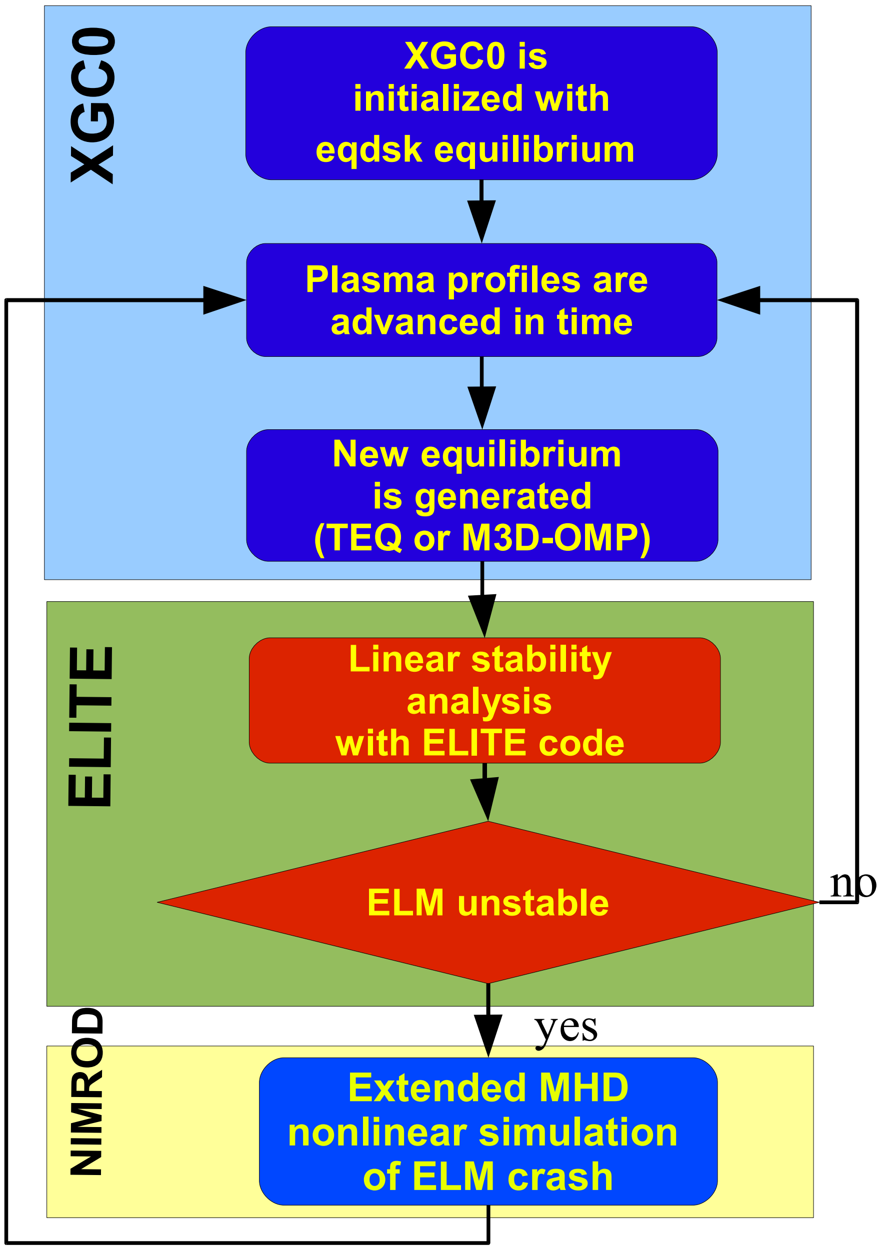

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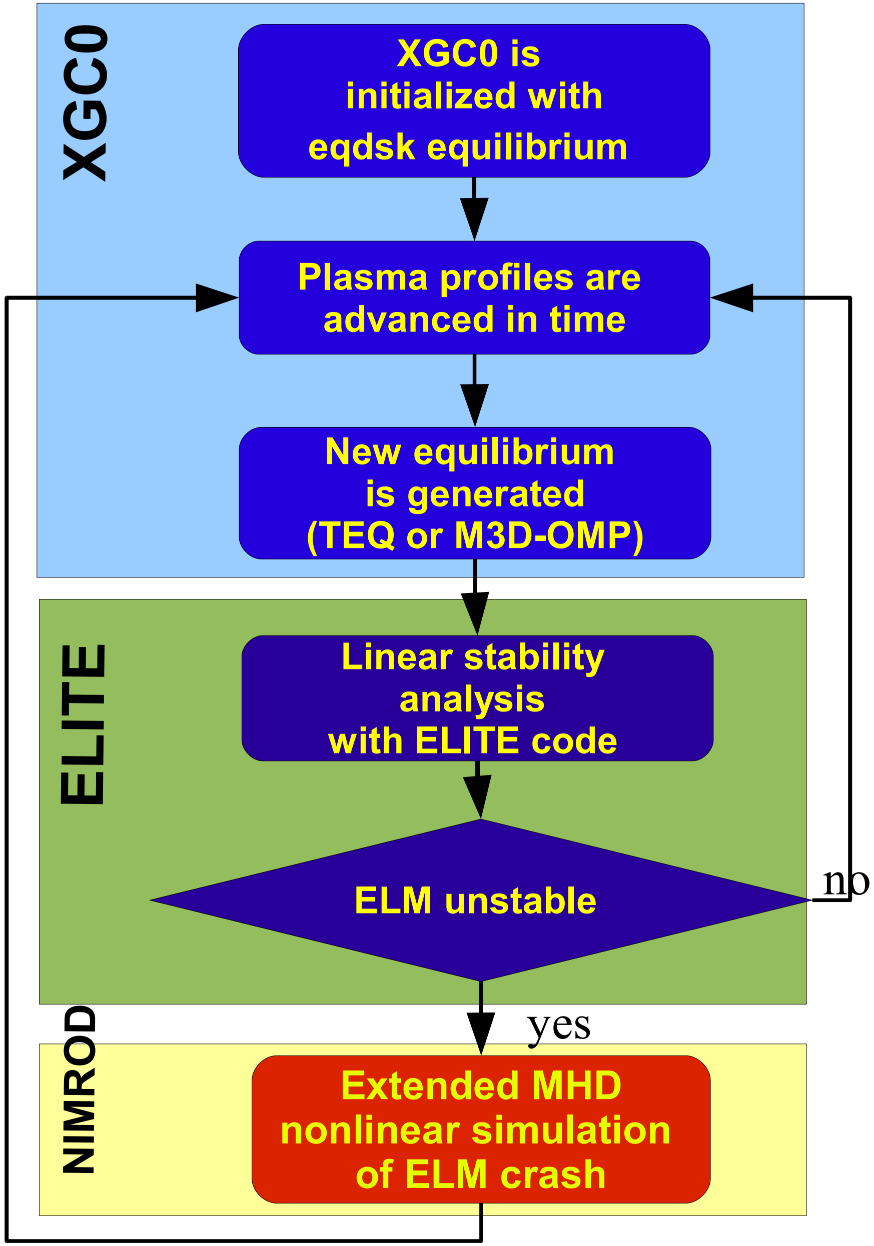
Extended MHD nonlinear simulation of ELM crash

Modeling of ELM Crash with NIMROD Code

The CEMM NIMROD code for extended nonlinear MHD uses

- High-order finite element representation of the poloidal plane:
  - Accuracy for MHD and transport anisotropy at realistic parameters: S>10^6, $\chi_{||}/\chi_{perp}$>10^9
  - Flexible spatial representation
- Temporal advance with semi-implicit and implicit methods
  - Multiple time-scale physics is described from ideal MHD (μs) to transport (ms) time scales



Modeling of ELM Crash with NIMROD Code

- **The NIMROD code numerically advances the resistive MHD equations in 3D geometry**

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

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi_{visc}$$

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

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B} \qquad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} + \kappa_{divb} \nabla\nabla \cdot \mathbf{B}$$

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J}$$

Modeling of ELM Crash with NIMROD Code

- In addition to previously added non-ideal effects, NIMROD allows two-fluid treatment
    - Hall and diamagnetic terms in Ohm’s law
    - More complete stress tensor in momentum equation

$$\rho\left(\frac{\partial \mathbf{V}}{\partial t}+\mathbf{V}\cdot\nabla\mathbf{V}\right)=-\nabla p+\mathbf{J}\times\mathbf{B}-\nabla\cdot\Pi_{visc}-\nabla\cdot\Pi_{\|_i}-\nabla\cdot\Pi^{gv}$$

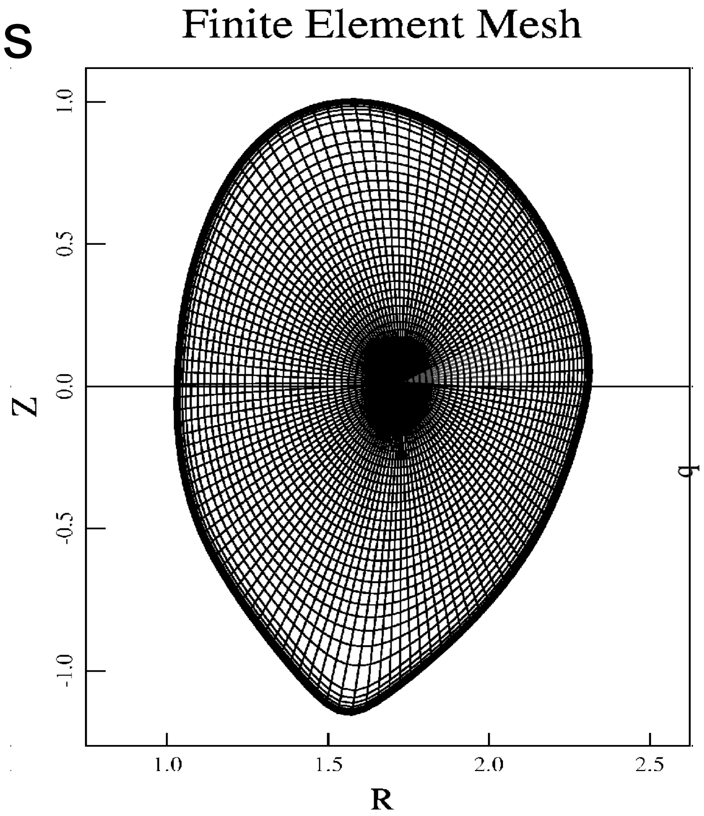
$$\mathbf{E}=-\underbrace{\mathbf{V}\times\mathbf{B}}_{\text{Ideal MHD}}+\underbrace{\frac{1}{ne}\left(\mathbf{J}\times\mathbf{B}-\nabla p_e-\nabla\cdot\Pi_{\|_e}\right)}_{\substack{\text{Two-fluid effects}\\ \text{(Hall + diamagnetic)}}}+\underbrace{\eta\mathbf{J}}_{\text{Resistive MHD}}$$

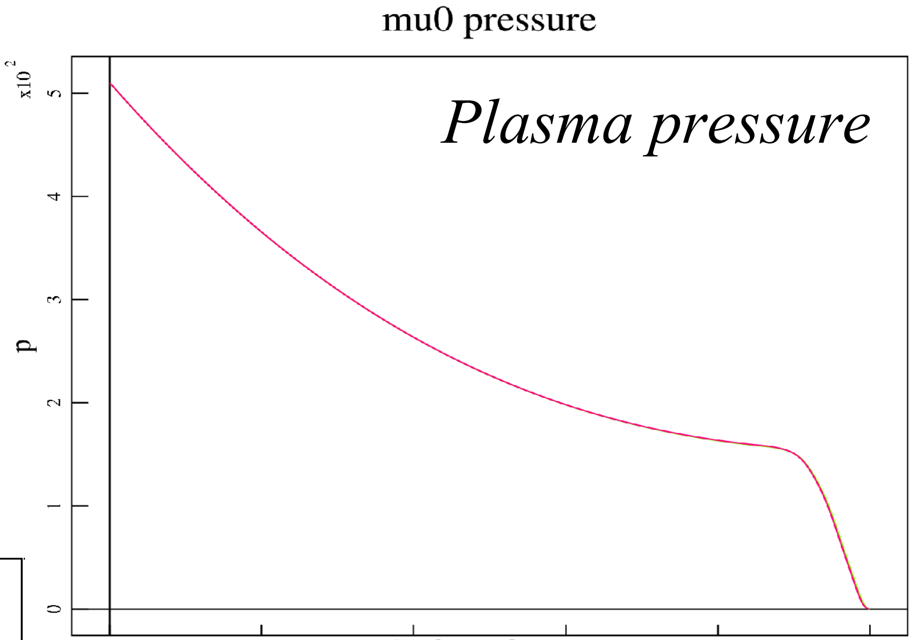
$$+\,\text{Equations for } p_i \text{ and } p_e, + \text{closures}$$

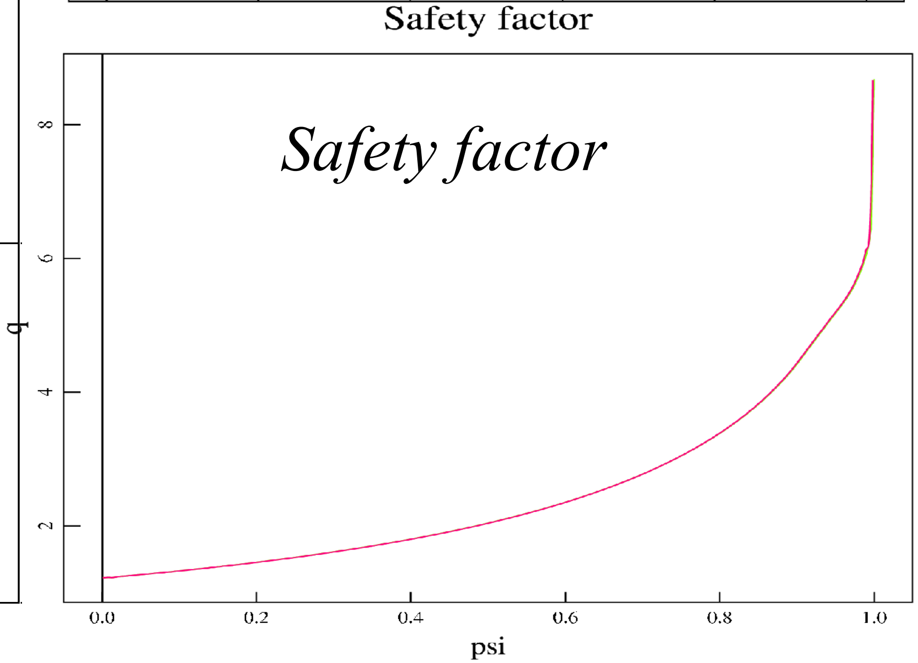
$$\Pi^{gv}=\frac{p}{4\Omega}\left[(\mathbf{b}\times\mathbf{W})\cdot(\mathbf{I}+3\mathbf{bb})+\text{transpose}\right] \qquad \mathbf{W}=\nabla\mathbf{V}+\nabla\mathbf{V}^T-\frac{2}{3}\mathbf{I}\nabla\cdot\mathbf{V}$$

NIMROD Simulation for DIII-D Discharge 96333

- NIMROD generates grid that is packed near the separatrix
  - Typical resolution used in this simulations is 40x160 with polynomial degree of 4
- 22 toroidal modes are considered

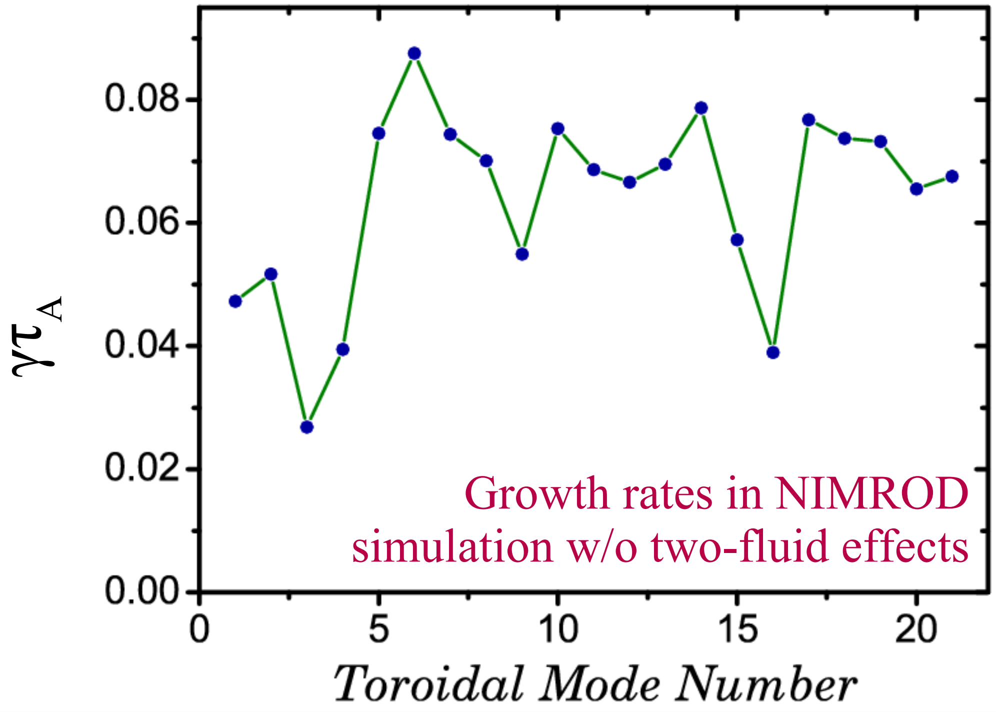




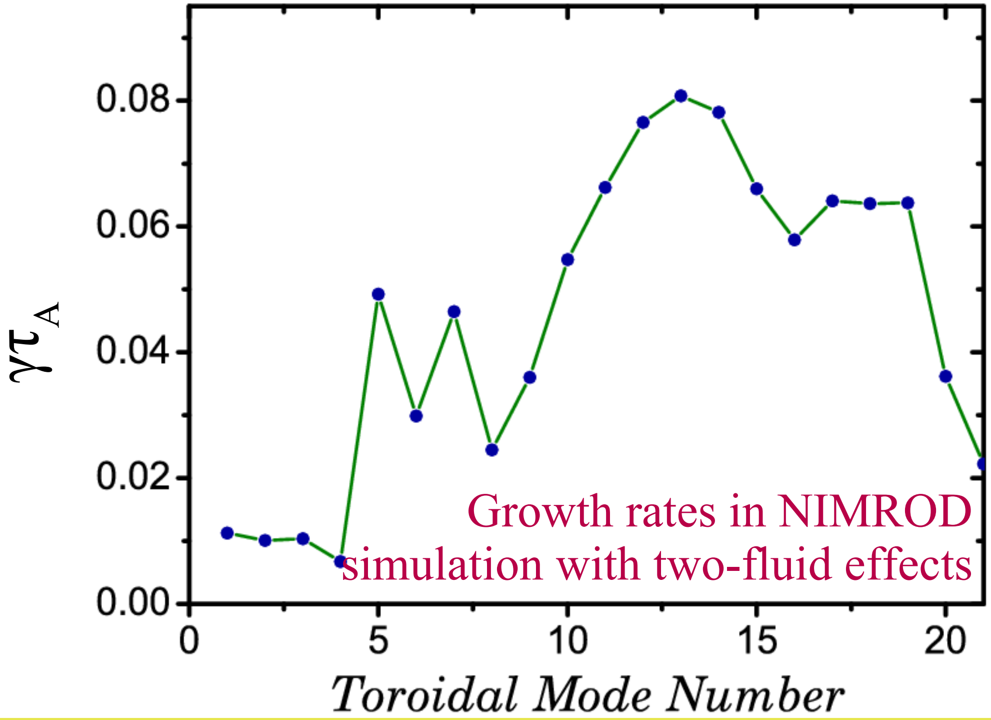


NIMROD Simulation for DIII-D Discharge 96333

- Nonlinear coupling between different toroidal modes in NIMROD simulations without two fluid effect leads to strong peaking of high toroidal modes numbers
  - **As result, simulations without two fluid effects are not resolved toroidally**
- Two-fluids effects are important in this simulations
  - **Effect of diamagnetic stabilization** $\omega_{*e,i} = \frac{c}{q_{e,i} n B^2} k_\theta \left(\boldsymbol{B} \times \nabla p_{e,i} \right)_\theta$



Growth rates in NIMROD simulation w/o two-fluid effects

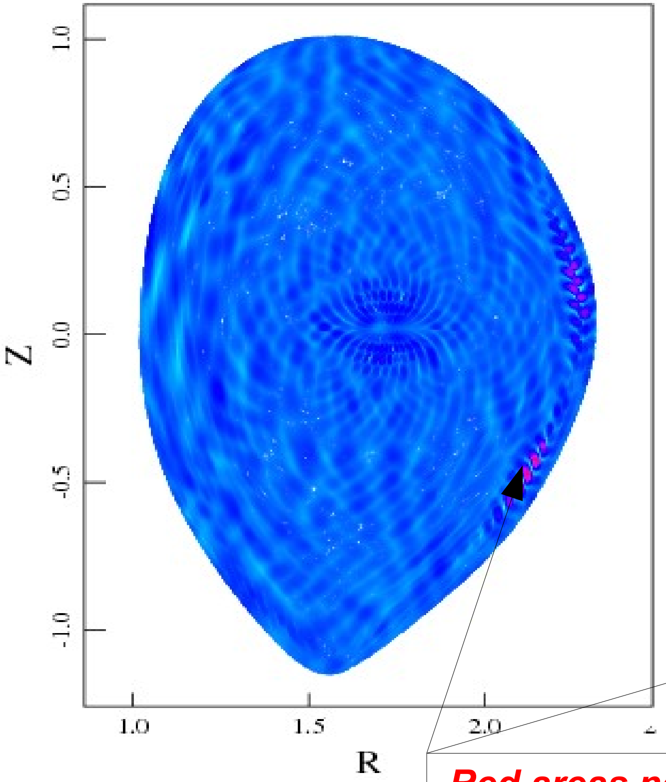


Growth rates in NIMROD simulation with two-fluid effects

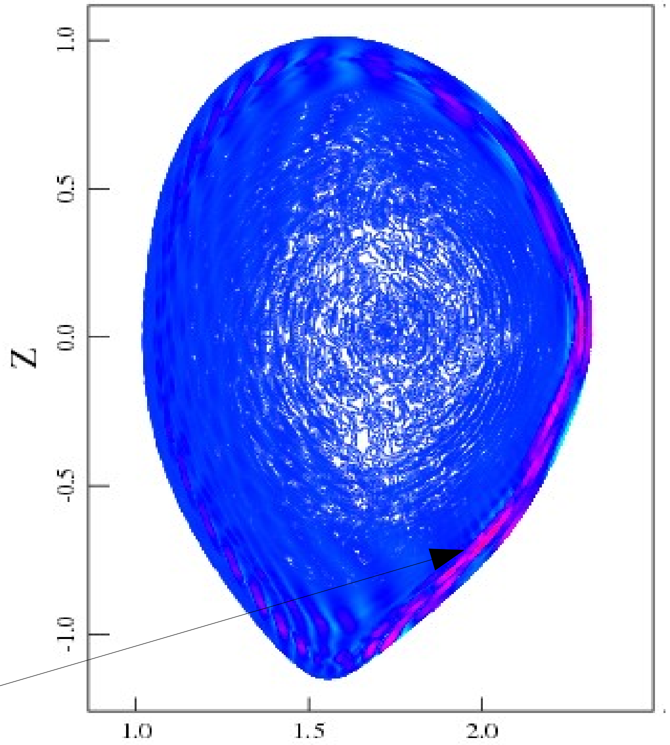
Modeling of ELM Crash with NIMROD Code

Simulation of temperature contour plots during an ELM crash in DIII-D discharge 96333

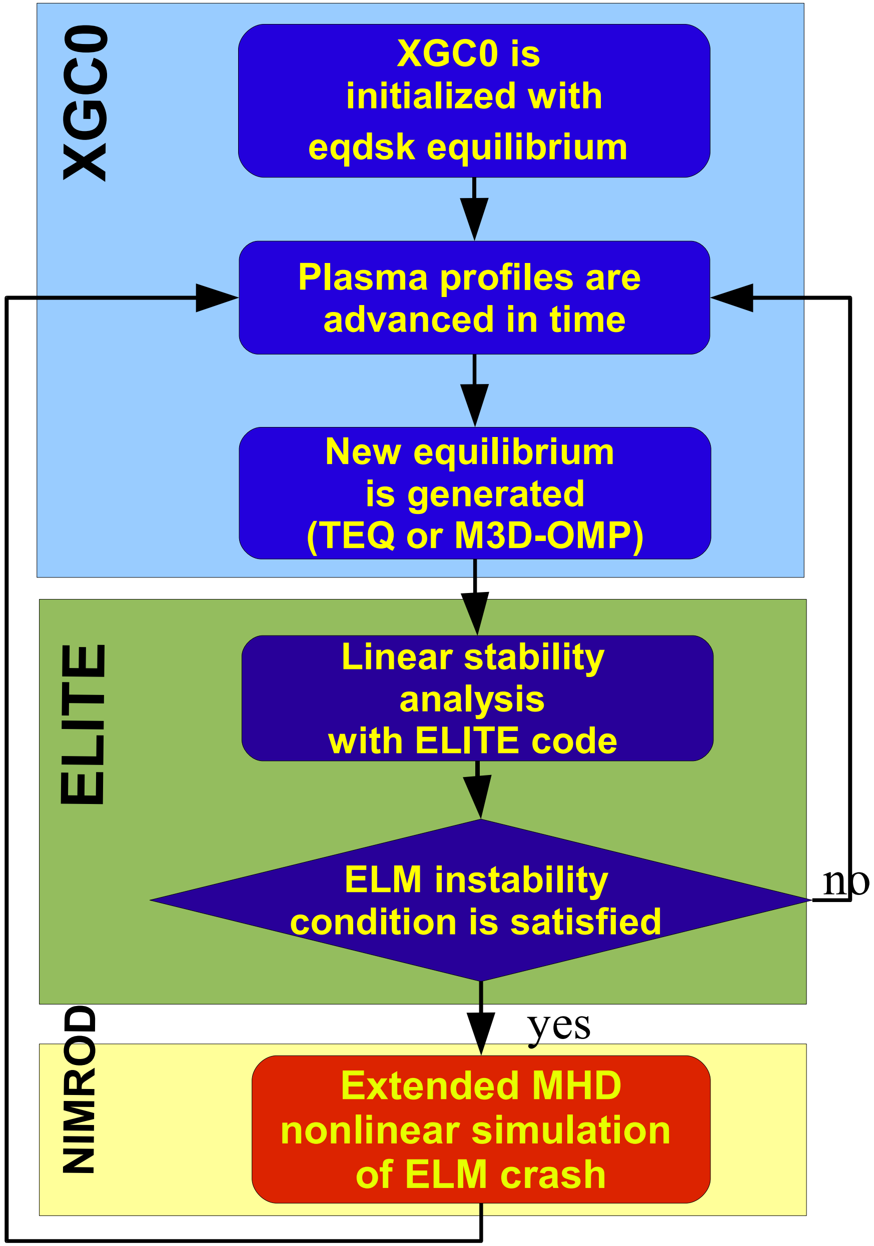
Initial (linear) stage of ballooning instability that leads to an ELM crash



Nonlinear stage of instability with ELM filaments that are strongly sheared by poloidal flow



Red areas near the separatrix correspond to large perturbations that are associated with development of an ELM crash



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ELITE

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ELM instability condition is satisfied

no

yes

NIMROD

Extended MHD nonlinear simulation of ELM crash

Summary

- **ELM cycle is modeled with the extended MHD NIMROD code coupled with the kinetic XGC0 code**
  - Filament-like structures are observed at the plasma edge
    - It is found that two-fluid are important for these simulations
- **Several codes are applied in the relevant range of parameters and results are cross-coupled**
  - Kinetic code XGC0 to follow the dynamics of H-mode pedestal recovery
  - Ideal MHD stability ELITE code to check peeling-ballooning stability conditions in the H-mode pedestal region
  - Extended MHD code NIMROD to study an ELM crash
- **ELM modeling is computationally challenging because of**
  - Wide range of time and spatial scales involved
  - Problem is highly anisotropic and stiff