**Long-time simulation and V&V components of the ISEP (Integrated Simulation of Energetic Particles in Burning Plasmas) project**

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### ISEP Introduction

- **Motivations**
  - EP (Energetic Particle) confinement is a critical issue for self-heated ignition experiments such as ITER – ignition requires good EP confinement
  - These can degrade overall plasma confinement and threaten the integrity of the wall and plasma-facing components
  - EPs => significant fraction of the plasma energy density in ITER. EPs can influence microturbulence responsible for turbulent transport of thermal plasmas and macroscopic magnetohydrodynamic (MHD) modes potentially leading to disruptions
  - Ignition regime plasma confinement with α-particle heating: one of the most uncertain issues for extrapolating from existing devices to ITER.

- **Objectives**
  - To improve physics understanding of EP confinement and EP interactions with burning thermal plasmas through exa-scale simulations
  - To develop a comprehensive predictive capability for EP physics
  - To deliver an EP module incorporating both first-principles simulation models and high fidelity reduced transport models to the fusion whole device modeling (WDM) project.

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### Energetic particle instabilities – V&V challenges

- The EP-driven Alfvén spectrum typically includes many unstable modes
  - Which mode dominates is model dependent and sensitive to profiles
  - A variety of different EP stability models have been developed (see below)
  - The most important profiles determining AE stability (n_{f,AE}, E_{AE}, q-profile) are not measured directly, but inferred from reconstruction or modeling
  - Fast ion profiles are “sculpted-out” over time by AE instabilities

### ISEP computational models

- **GTC**
  - First-principles, multi-physics, global gyrokinetic particle-in-cell (PIC) model with applications to microturbulence, meso-scale EP instabilities, MHD modes, RF (radio-frequency) heating and neoclassical transport
  - Adapted to peta-scale and emerging exascale platforms
  - MPI, OpenMP and GPU parallelism

- **GYRO**
  - Comprehensive continuum (Eulerian) electromagnetic global 6D gyrokinetic model
  - Includes full physics features needed to realistically simulate turbulence and transport in experimental tokamak discharges

- **FAR3D/TAEFL**
  - High fidelity reduced stability model using Landau-fluid closures to include resonant drives and Padi approximations to include finite gyro-radius effects
  - Time evolution and direct eigenvalue options

### Collaborating models

- **GEM – gyrokinetic 6D PIC**
  - EUTERPE - global, electromagnetic gyrokinetic PIC
  - ORBS - linear/nonlinear gyrokinetic PIC
  - MEGA – kinetic/MHD hybrid
  - M3D-K – kinetic/MHD hybrid
  - NOVA-K – linear hybrid kinetic/MHD

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### Previous GSEP verification and validation activities

- Directed toward the simulation of RSAE modes in the DIII-D tokamak (discharge #142111) with time-evolving frequencies
  - 3 codes: GTC, GYRO, and TAEFL – linear analysis

### Current ISEP verification and validation activity

- Directed toward the simulation of RSAE and TAE modes in the DIII-D tokamak (discharge #142111) with time-evolving frequencies
  - 8 codes: GTC, GYRO, FAR3D, GEM, EUTERPE, ORBS, MEGA, NOVA
  - Both linear and nonlinear simulations are in progress

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### ISEP Verification and Validation Activities

- **Nonlinear Alfvénic instability simulation is important for understanding EP transport effects and heat loads on plasma-facing components (PFC)**
  - Critical gradient (time average effect): EP profiles evolve to be near marginal stability => profiles don’t change with increasing power
  - Long-time nonlinear effects: variation, intermittency about critical gradient point => instantaneous losses exceed time average and can cause PFC damage

- **Long-term intermittency example:** multi-mode nonlinear gyrofluid simulation of #142111 for fixed q-profile with source balanced against losses for 10^5 Alfvén times (~ 3 msec)

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### Conclusions and future work

- **Verification and Validation**
  - ISEP and the previous GSEP projects have developed close connections with fusion experiments, such as DIII-D, for successful V&V activities
  - In addition to the primary ISEP models, we have engaged with outside EP modeling codes
  - Recent linear stability verification will be extended to the nonlinear regime

- **Long-term nonlinear simulations**
  - Multiple AE modes have been followed for 10,000 Alfvén times
  - Extension to recent DIII-D transport analysis case
  - Connection with critical gradient modeling
  - Source/sink balancing models will be further developed