Long-time scale 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 (**E**nergetic **P**article) confinement is a critical issue for self-heated ignition experiments such as ITER – ignition requires good EP confinement
  - EPs can excite mesoscale EP instabilities => drive large EP transport.
  - 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.

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_{fast}, E_{fast}, q-profile) are not measured directly, but inferred from reconstruction or modeling
- Fast ion profiles are "sculpted-out" over time by AE instabilities

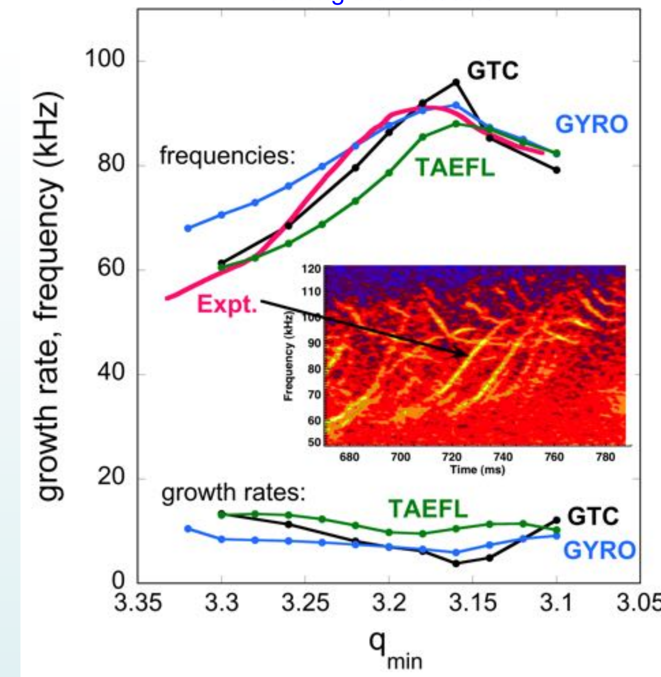
ISEP computational models

- **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 δ*f* 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 eigensolver options
- **Collaborating models**
  - GEM – gyrokinetic δf PIC
  - EUTERPE – global, electromagnetic gyrokinetic PIC
  - ORB5 – linear/nonlinear gyrokinetic PIC
  - MEGA – kinetic/MHD hybrid
  - M3D-K - kinetic/MHD hybrid
  - NOVA-K – linear hybrid kinetic/MHD

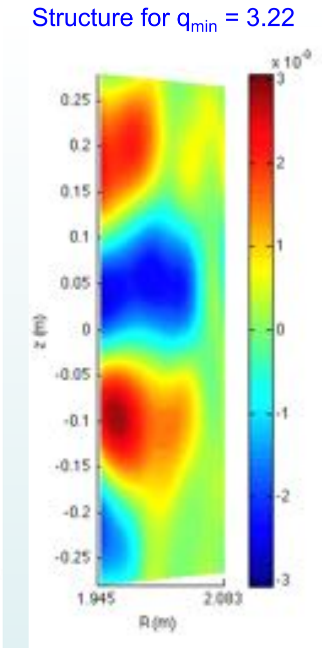
ISEP Verification and Validation Activities

- **Previous GSEP verification and validation activity**
  - 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
  - D. A. Spong, E. M. Bass, W. Deng, W. W. Heidbrink, Z. Lin, B. Tobias, M. A. Van Zeeland, M. E. Austin, C. W. Domier, N. C. Luhmann, Jr., "Verification and validation of linear gyrokinetic simulation of Alfven eigenmodes in the DIII-D tokamak," Phys. Plasmas Vol. 19 (2012) 082511-1.

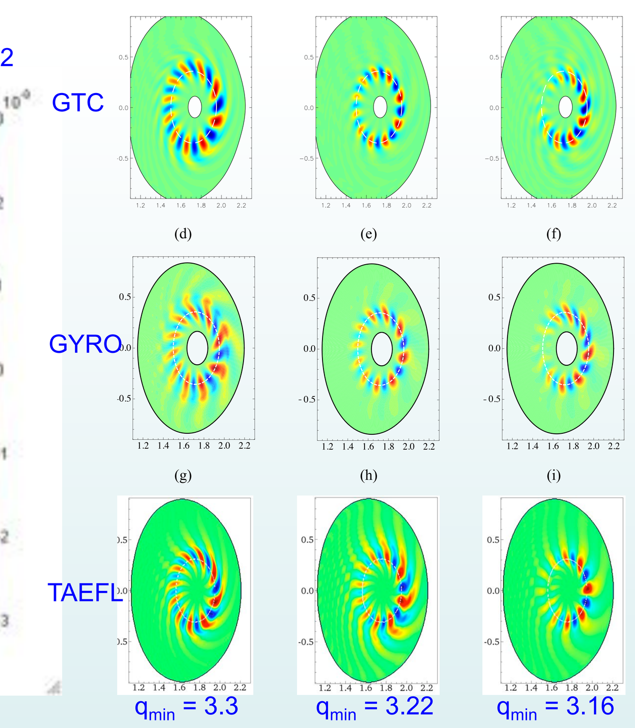
Frequency/growth rate variation with q_{min} among the 3 models



Measured mode Structure for q_{min} = 3.22

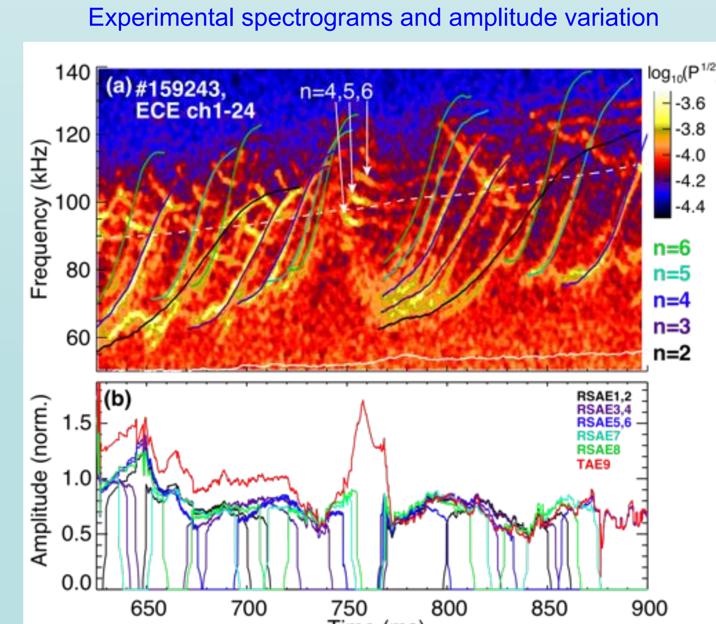


Predicted 2D mode structures

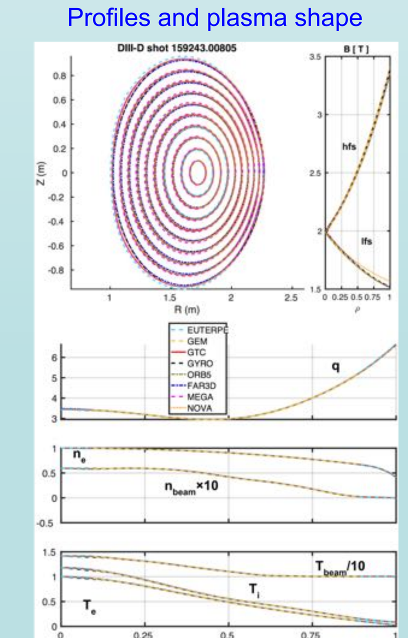


- **Current ISEP verification and validation activity**
  - Directed toward the simulation of RSAE and TAE modes in the DIII-D tokamak (discharge #159243 which featured comprehensive stability and fast ion transport diagnostics
    - C. Collins, W. Heidbrink, M. Podesta`, R. White, G. Kramer, D. Pace, et al., "Phase-space dependent critical gradient behavior of fast-ion transport due to alfv´en eigenmodes," Nuclear Fusion, vol. **57**, no. 8, p. 086 005, 2017.
  - 8 codes: GTC, GYRO, FAR3D, GEM, EUTERPE, ORB5, MEGA, NOVA
  - Both linear and nonlinear simulations are in progress

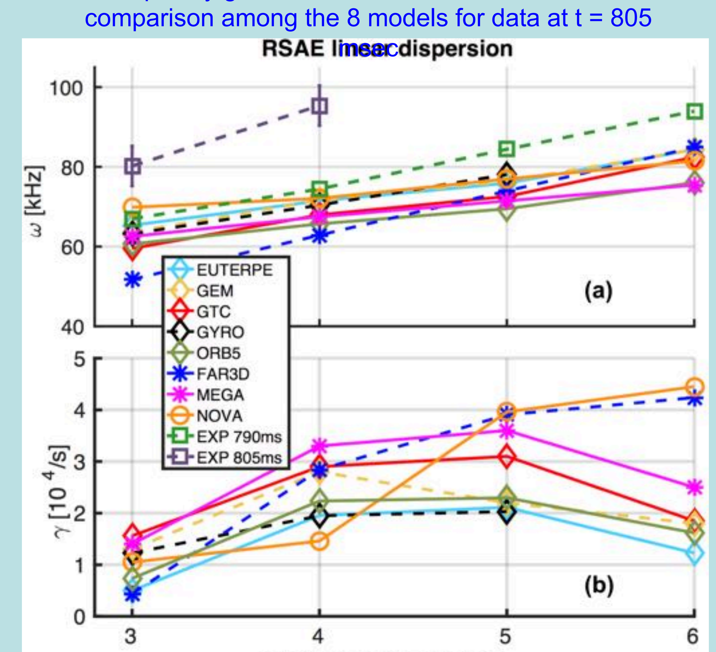
Experimental spectrograms and amplitude variation



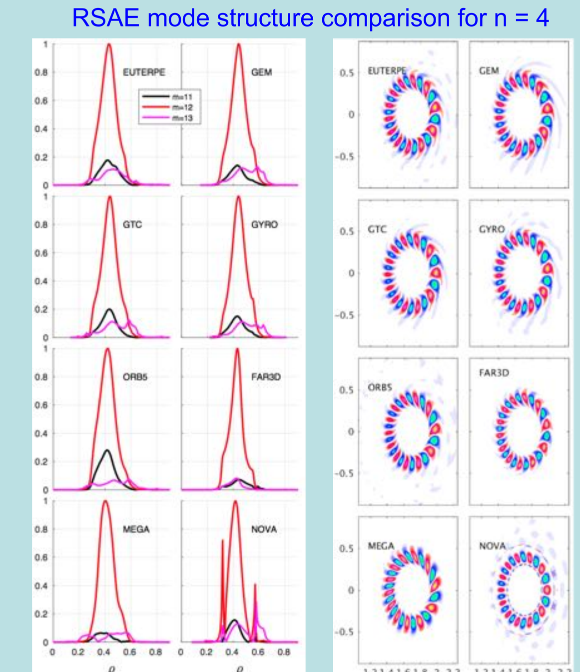
Profiles and plasma shape



Frequency/growth rate vs. toroidal mode number comparison among the 8 models for data at t = 805



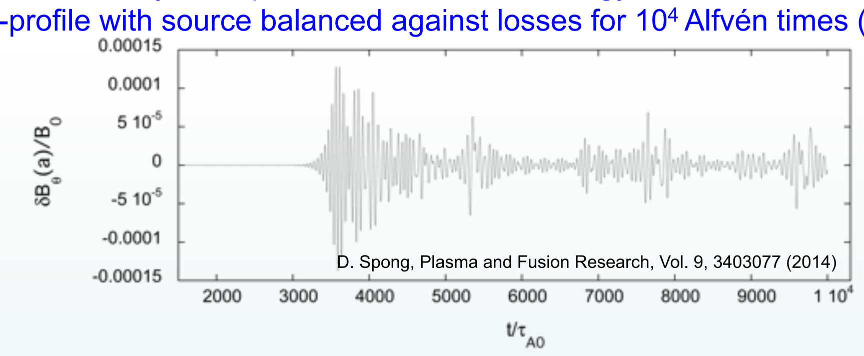
RSAE mode structure comparison for n = 4



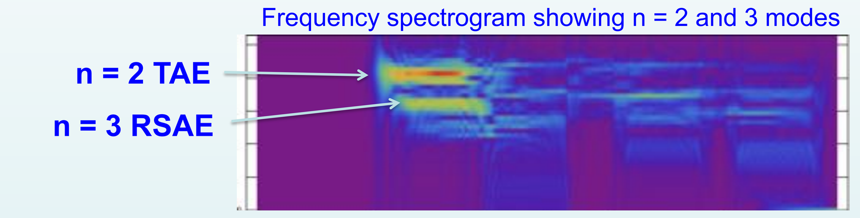
Long-time simulation of energetic particle instabilities

- **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 => stiff transport regime => 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

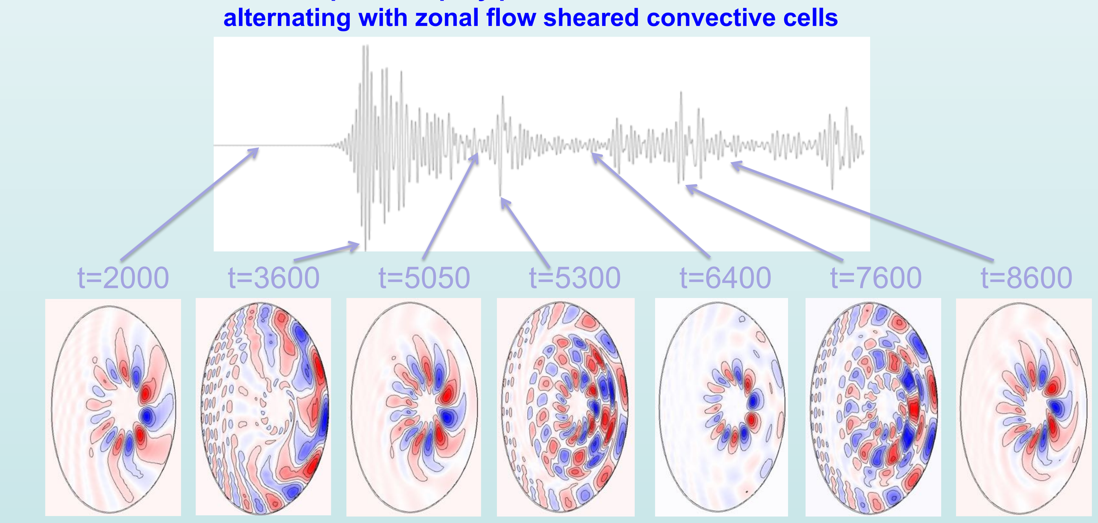
Long term intermittency example: multi-mode nonlinear gyrofluid simulation of #142111 for fixed q-profile with source balanced against losses for 10^4 Alfvén times (~ 3 msec)



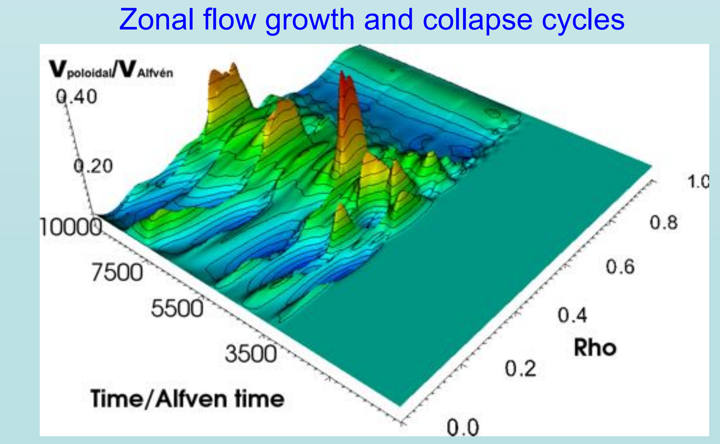
Frequency spectrogram showing n = 2 and 3 modes



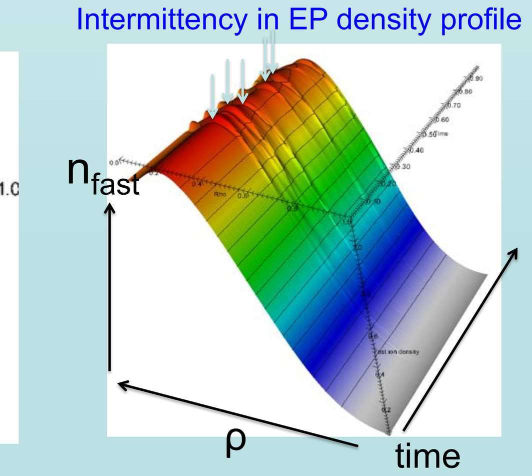
Intermittent predator/prey phenomena: coherent structure alternating with zonal flow sheared convective cells



Zonal flow growth and collapse cycles



Intermittency in EP density profile



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**
  - Mutiple 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 deveolped