Summary of Progress in Theory & Computation

16th IAEA Technical Meeting on EPs
& Theory of Plasma Instabilities

3-6 September 2019, Shizuoka City, Japan

Andreas Bierwage / QST, Japan

EX-M-TH Statistics*

*Somewhat subjective

- "M" = Descriptive theory, predictive
  modeling, numerical exp., quantitative predictions, data analysis, synthetic diagnostics, ITER, DEMO
- "TH" = Explanatory theory & num. simulation
  includes code development, V&V

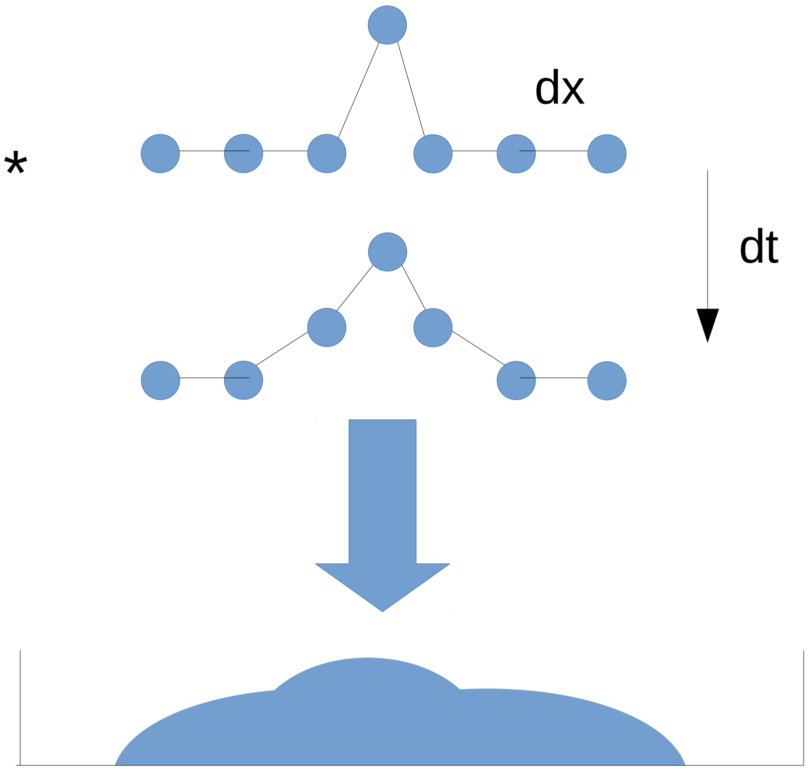
• Invited (14):	EX: 8	M: 2	TH: 4
• Oral (22):	EX: 10	M: 4	TH: 8
• Poster I (29):	EX: 12	M: 11	TH: 6
• Poster II (28):	EX: 4	M: 6	TH: 18
• Total (93):	EX: 34	M: 23	TH: 36

(3 cancellations)

How theory+sim. works (not real world!)

- Similar result can be realized in many ways. → Reduced mdl.
- But what if we want to know the “truth”?
- Motivating example:
  Mode structure formation process via fast waves [I-6 Tykhyy]

- Reduced MHD:
  No physical waves propagating radially.
  That time scale is assumed infinitely fast.*
  → Mode formation in sim. is purely
  numerical response to
  physical model constraints.



- Full MHD:
  Fast waves carry information radially
  in finite time in a (more) physical way.
- GK: KAW … Fully kin.: Langmuir waves
  have even more degrees of freedom.
- Relevant for explaining and quantifying <u>processes</u> in true form
  (e.g. “channeling”, fast reconnection, rapid NL processes)

*Thanks to B. Breizman

Codes: Development, feasibility demonstration, V&V

1. Monte Carlo

- [P2-31 Ward] LOCUST-GPU
  - Monte Carlo orbit following
  - Tested; available with Python wrapper for IMAS
  - Planning:
    - HiFi RMP dataset
    - parametrized "loss database" for quick look-up of ptcl. deposition on wall w/o simulation
- [P2-27 Fitzgerald] HALO
  - Monte Carlo orbit following with fluctuating fields
  - Perturbative wave-particle interaction model of HAGIS added to LOCUST-GPU

Codes: Development, feasibility demonstration, V&V

2. Hybrid

- [P2-4 Vlad] HYMAGYC
  - Hybrid lin. full MHD + NL GK PIC
  - First runs with full set of new features: shaped plasma, FLR, incl. $\delta A_\perp$
  - Begin application to NLED AUG, DTT test scenario
  - Planning benchmarks (MEGA, …)
- [O-13 Seki] MEGA
  - Hybrid NL full MHD-GK PIC
  - Validating long-time sims of bursting modes in LHD

Codes: Development, feasibility demonstration, V&V

3. Gyrofluid, gyrokinetic

- [P2-15 Spong] TAEFL / FAR3d
  - Gyro-Landau fluid
  - Includes sources & sinks, nonperturbative effects (n=0 NL response, chirping, mode distortion)
  - Demonstrated feasibility of long-time sim of steady/ bursty EP-driven AEs → 50k Alfven times (~10 ms)
- [P2-2 Hayward-Schneider] [P2-3 Vannini] ORB5
  - Global full-radius full-f GK PIC
  - ITER 15 MA: linear TAE benchmark vs. LIGKA, m_e scan, n-spectrum, KAW propagation
  - AUG: testing continuum damping, e- Landau damping
  - Begin NL runs (annular region, equilibrium frozen)

Legend

Research methods & models

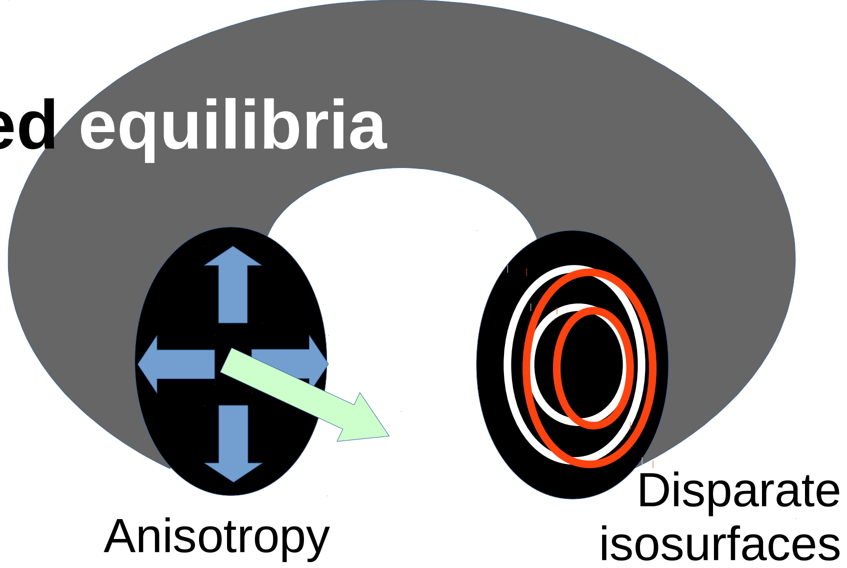
Background, internal & external forcing, exhaust

- **Equilibrium, "zonal structures"**: "n=0" (arb. k in R,Z) "w~0" (slow evol.) F0 (bulk + EP + imp.) Rotation, "barriers"
- **Internal & external forcing**: RMP, ECH, ICRH, beams torque, pellets
- **Fusion, fuelling, exhaust**: Fuelling, reactions, ash, heat load, ITER, DEMO

Collective fluctuations

- **Micro-turbulence**: Broad-band fluct., ES-DW...EM-DAW
- **Lin. waves, discrete modes**: Continua, Kink … AE … IC
- **Transient phenomena**: Chirps, bursts, core & edge relax., disruptions
- **NL solitary structures, vortices**: vortices, filaments, islands, BGK modes ("holes & clumps")

Generalized equilibria



MHD

[P2-17 Hole]

- (Tor.) flow and pressure anisotropy
- Mapping techniques (e.g. to fix q)
- Applications: Ballooning stablility, ITER flux geometry & continua

2-fluid analytical + numerical.

[P2-16 Ito]

- 2-fluid equilibrium with
  - toroidal + poloidal flow
  - ion FLR, P anisotropy
  - parallel heat flux
- Analytical solutions for $v \sim v_A$ and $v \sim c_S$ limits

Future: Equiilibria consistent with EM GK models.
→ Needed for NL sims at high beta (...DEMO reactor)

Equilibrium, "zonal structures"

Internal & external forcing

Fusion, fuelling, exhaust

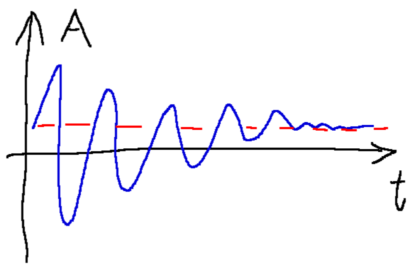
Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

NL solitary structures, vortices

EP effect on residual ZF



Polarization shielding (FLR, class.)
enhanced by magnetic drifts (FOW, neoclass)

Analytical Bounce-kin.

[O-6 Hahm, T.S.]

- Showed that long-wavelength high-aspect-ratio theory is valid for arbitrary isotropic F0
- 10% isotropic Maxwellian alphas
  → 10% change in R_{ZF} with kρ ~ 0.1

Analytical + numerical.

[P1-11 Lu, Zhixin]

- Effect of anisotropy
  → enhancement or reduction depending on pitch
- Applied to beam-driven AUG
  → 5-10% change in R_{ZF}

Equilibrium, “zonal structures”

Internal & external forcing

Fusion, fuelling, exhaust

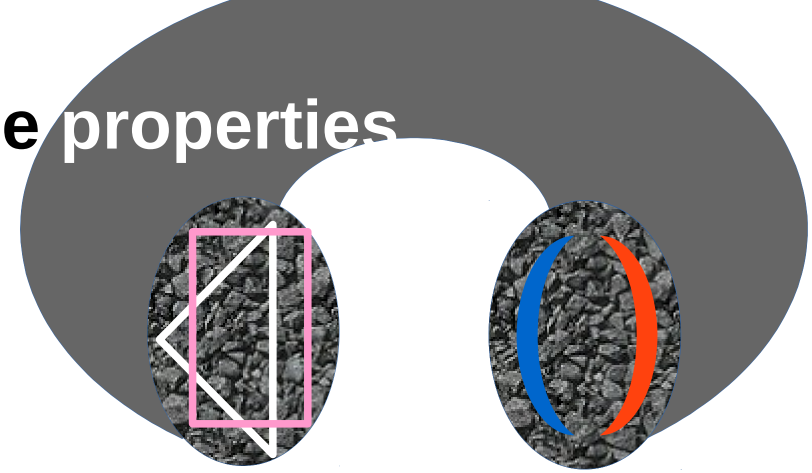
Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

NL solitary structures, vortices

Turbulence properties



Linear full-f GK

[I-4 Wang, Wei] GKNET

- Parameter survey of ITG and TEM stability depending on elongation & triangularity
- Confirmed stabilizing trends, identified mechanisms: - effective T gradient (ITG, TEM)
  - magnetic shear effects (TEM)

NL full-f GK

[P2-18 Asahi] GT5D

- Convective cells (CS: m≠0, n=0) due to passing e- response
- CS enhances role of magnetic drift and reduces role of ExB drift for energy transport

NL extended MHD

[P1-21 Cho, YoungWoo]

- Investigate ITB formation by looking at transient radial corrugations (→ traffic jam model)

Equilibrium, "zonal structures"

Internal & external forcing

Fusion, fuelling, exhaust

Micro-turbulence

Lin. waves, discrete modes

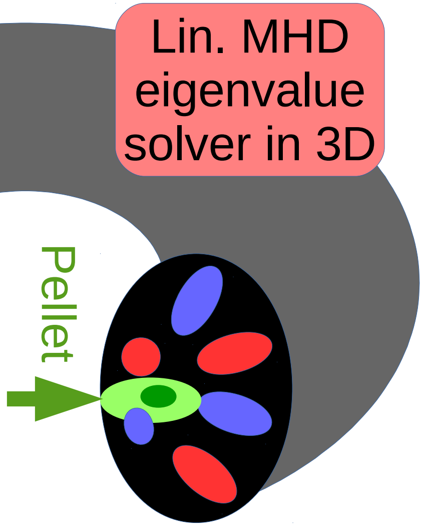
Transient phenomena

NL solitary structures, vortices

Pellets

Pellet cloud diagnostics via MHD spectroscopy

Lin. MHD eigenvalue solver in 3D



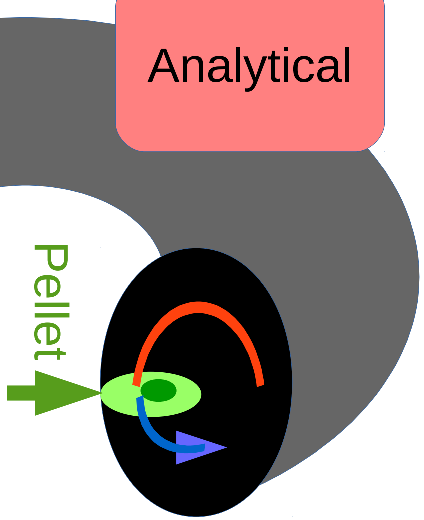
[O-4 Oliver] Stellgap, AE3D

- Calculated Alfven continua and eigenmodes for axisymm. plasma with 3D density pert.
- Toroidal modulation ignorable, lowest order (m=1) poloidal modulation of v_A kept

→ shift and sweeping of TAE freq. tells us about n_i and homogenization rate

Runaway electron (RE) mitigation with high-Z pellets (considered for ITER)

Analytical



[O-10 Breizman]

- Revisit RE passing through ablating pellet
- Find that e- magnetization has large effect on pwr. deposition
- Pellet radius power law for ablation rate is robust, but scalar factor changed by > 2

→ Kin. treatment (elastic scattering) of ablation rate is important

RMP

TAE control with RMP
(for scenarios with weak plasma edge shielding)

Global NL MHD-PIC hybrid

[P1-4 Gonzales-Martin] MEGA
[O-14 Garcia-Munoz] AUG experiment

- Computed plasma response to RMP:
  → n=2 kink (no islands)
- Demonstrated effect of RMPs on EPs and on EP-driven AEs in AUG

Equilibrium, "zonal structures"

Internal & external forcing

Fusion reactor, exhaust

Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

NL solitary structures, vortices

EP ↔ turbulence interactions

AUG, JET experiments show:
T_i increases when EPs are present … Why?

Local NL EM GK simulation

[I-3 Siena] GENE
- Applied to JET, ignoring ICRF
- Key: Finite beta
  → Turbulence becomes electromagnetic (EM)
  → Stable AEs are then part of the turbulence, acting as energy sink
- EPs: Reduce AE damping
  → Larger AE = more eff. energy sink for ITG
  → Multi-n AE turbulence = additional NL drive for zonal field
- This is one possible explanation.

Global NL MHD-PIC hybrid

[P1-24 Kang, ByungJun] GKW
- Excited fast-ion-driven electron drift instability excited via precession drift reversal

Equilibrium, “zonal structures”

Internal & external forcing

Fusion reactor, exhaust

Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

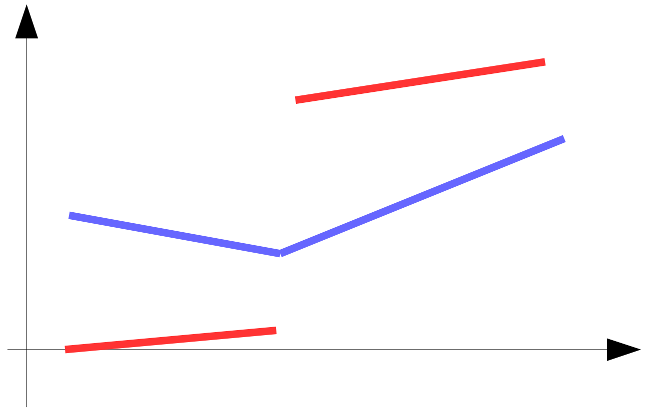
NL solitary structures, vortices

EP ↔ kink interactions ("q>1 off-axis fishbone")

Local NL EM GK simulation

[P2-13 Cai, Huishan] M3D-K

- Consider reversed shear configuration with m/n=2/1 resistive double tearing mode (DTM)
- Found: Increasing β_{EP} stablizes zero-freq. DTM and destabilizes oscillating kink-like mode between pair of q=2 rational surf. around q_{min}
- Driven by EP precession resonance



Equilibrium, "zonal structures"

Internal & external forcing

Fusion reactor, exhaust

Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

NL solitary structures, vortices

SAW ↔ electron interaction

Global NL MHD-PIC hybrid

[O-15 Wang, Jialei] MEGA

- Sim. with large energetic electron population (β_{EP}~ 1%).
- Case study: Varied backgound beta,
  q profile, β_{EP} peak location
- Demonstrated ways how EE interact with
  - fast-ion-driven and EE-driven TAE (finite k||), precession)
  - EAE (k||=0, transit)

Equilibrium, “zonal structures”

Internal & external forcing

Fusion reactor, exhaust

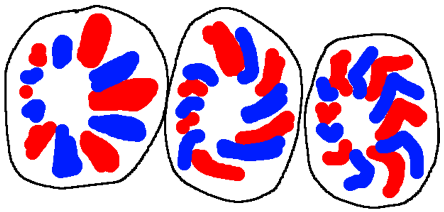
Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

NL solitary structures, vortices

Mode structure distortion



Full MHD WKBJ approx

[I-6 Tykhyy]

- Spatially separated source and sink (“spatial channeling”)
  → Produces spiral distortion as in DIII-D, NSTX
  → Relevant for mode saturation?

Perturbative δf sim.

[P1-26 Meng, Guo]

- Systematically designed model mode structure distortions
- Analyzed EP phase-space structures
- Demonstrated impact on growth (~10%), saturation (~20%) and EP transport (~10%)

Extended MHD theory

[P2-29 de Souza, Elfimov et al]

- Distortion of GAM continuum by EP effects accounted for by replacing Γ=5/3 with EP corrected factor
  → Modified accumulation point $(\psi,\omega)_{GAM}$ matches EGAM

Equilibrium, “zonal structures”

Internal & external forcing

Fusion reactor, exhaust

Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

NL solitary structures, vortices

Mode distortion & chirping

NL hybrid with kinetic bulk ions

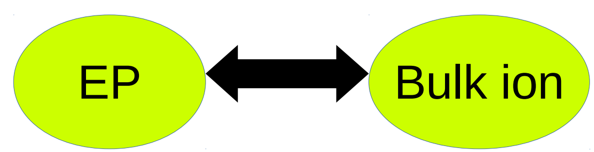
[P2-1 Wang, Xin] XHMGC
- Simulated chirping EPMs from TAE to BAE accumulation points
- Characterized dep. on pitch distrib. (isotr.,co,ctr)

Lagrangian FEM

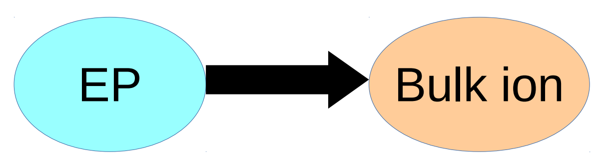
[P2-9 Hezaveh]
- Nonpert. model with coll. & drift
- Study long-range chirping of a GAE (cylindrical) driven by EPs (with toroidal effect)
- Characterized mode distortion & chirping rate, which exceeds $t^{1/2}$

NL hybrid with kinetic bulk ions

[P2-14 Wang, Hao] MEGA
- Steady EGAM:
  → Balanced energy transfer



- EGAM during NL structure formation or chirping:
  → Net bulk ion heating



Equilibrium, "zonal structures"

Internal & external forcing

Fusion reactor, exhaust

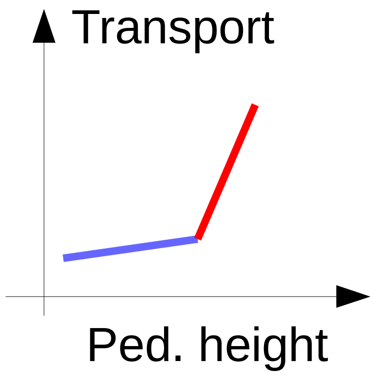
Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

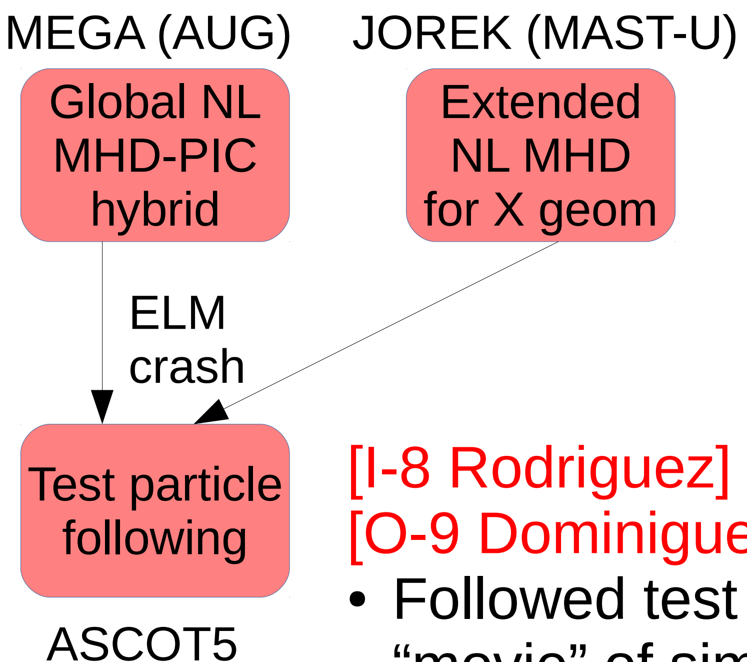
NL solitary structures, vortices

Pedestal crash (ELM) and effect on EPs



[P1-23 Seto] BOUT++

- Looked into n=0, ExB, turbulence interplay for varying pedestal height
- Found abrupt change in transport
  → Investigating role of damped oscillations



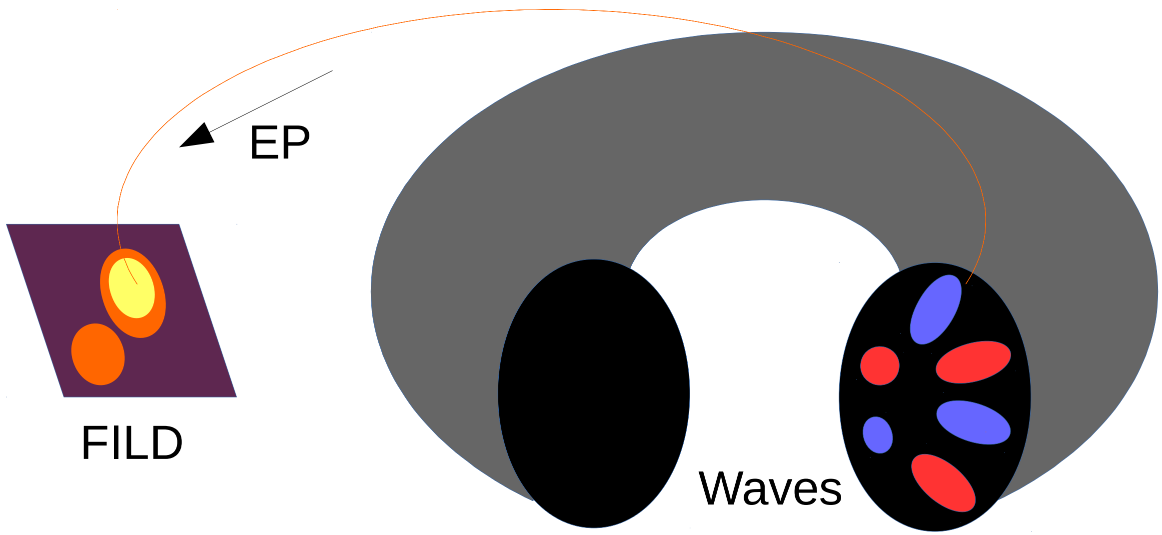
[I-8 Rodriguez] MEGA (AUG), JOREK (MAST-U)
[O-9 Dominiguez-Palacios] MEGA (AUG)

- Followed test particles while replaying "movie" of simulated ELM-crash
- Demonstrated capability to predict ELM-induced EP losses (e.g. synthetic FILD)

Applications of theoretical insight & state-of-the-art numerical methods: Specific predictive simulations

- Reduced model development
- Multi-physics multi-scale integrated codes
  1) separation of physics & scales
     → specialized codes solving “first principle” equations or reduced “empirical” models
  2) development and implementation of interfaces and workflows
- Synthetic diagnostics
- Validation
- Inverse problem, interpretation

Inverse problem, interpretation



Global NL MHD-PIC hybrid

[O-13 Seki] MEGA

- Reconstruct AE activity in LHD responsible for observed FILD signal

Equilibrium, “zonal structures”

Internal & external forcing

Fusion reactor, exhaust

Micro-turbulence

Lin. waves, discrete modes

Transient phenomena

NL solitary structures, vortices

Exp. studies now make heavy use of num. simulations for quantitative prediction and interpretation

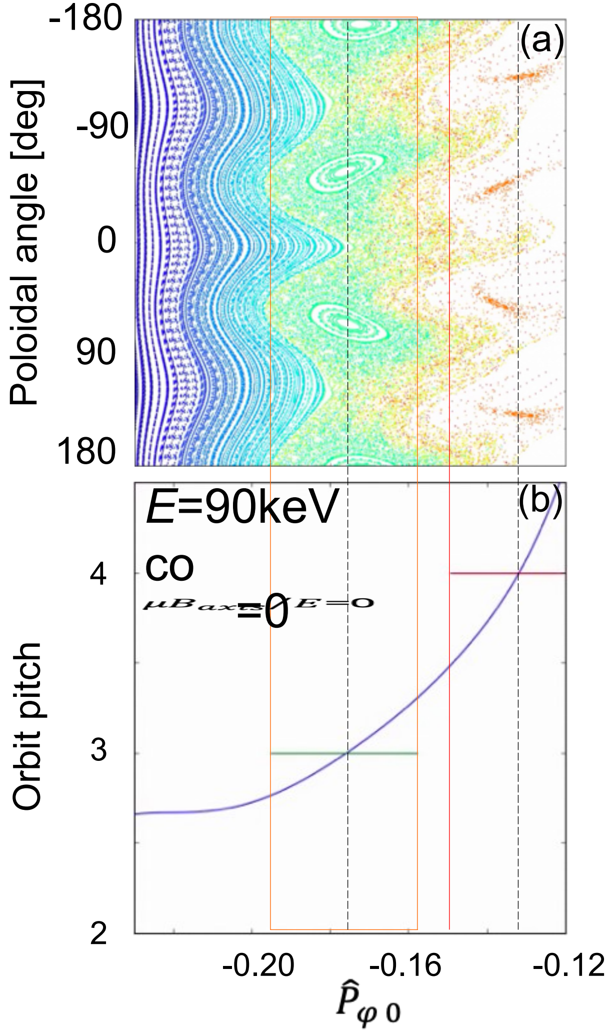
- Monte-Carlo codes/modules are routinely used in many studies (ASCOT, GNET, NUBEAM, TRANSP, …)
  and more are coming (LOCUST, HALO)
- GNET: Used intensively in Japan
  [P1-16 Yamamoto] [P1-18 Yamaguchi] [P1-19 Murakami] [P1-20 Kotera]
- EUTERPE: W7-X
  [O-17 Slaby] Tools for extracting mode info from noisy multi-mode signals, continua from arbitrary sim. models (e.g. including with flows).
- MEGA: hybrid code
  [P2-11 Adulsiriswad] Heliotron J
  [P2-12 Idouakass] LHD
- FAR3d: gyrofluid:
  [P1-1] Varela → Heliotron J and LHD
  [P1-3] Cappa → TJ-II stellarator

There are many more examples.

Need to reduce computational cost → Reduced models, integrated sim.

- Hole-clump B&B model application in exp. [I-14 Viktorov]
- Quaslinear, critical gradient, resonance broadaning predator-prey [O-22 Bass] [P2-30 Duarte] [O-20 Gorelenkov] RQB
- Kick model [I-11 Podesta] [O-5 Liu, Deyong] DIII-D [O-12 Cecconello] MAST

[P2-22 Shinohara] KSTAR 10-15% accurate estimate of island width Poincare plot



Dedicated to ITER / DEMO / BP

- Disruption mitigation high-Z pellet (improved model for effect on REs) [O-10 Breizman]
- Inward pinch for pellet fuelling (ion mixing mode, TEM) [P1-22 Yagi]
- Estimated neutron yield in Pre-DT ITER [P1-14 Polevio] (Not yet conclusive. Need improved description of NL dependence of S_n on local n_e, n_{Be}).
- Began Full-f GK AE simulation for ITER [P2-2 Hayward-Schneider]
- Generalized ITER equilib. with anisotropy (and toroidal flow) [P2-17 Hole]
- Critical gradient model for DIII-D scenario for ITER [O-22 Bass]
- Variations in fusion reactivity [P2-25 Matsuura] (After-glow plasma reactivity drop is delayed due to nuclear elastic scattering NSE besides coll. heating)

Results of many other studies are also relevant