# Plasma Science

## Co-Chairs

**Arnold Kritz** (Lehigh University)

**John Cary** (University of Colorado)

Commitee Members V. Chan (GA)

P. Drake (U Michigan)

G. Hammett (PPPL)

M. Peng (ORNL)

M. Rosen (LLNL)

S. Prager (U Wisconsin)

W. Tang (PPPL)

# Four Subtopical Discussion Groups

Turbulence and Transport

G. Hammett and P. Terry – Co-Chairs

(Magneto-) Hydrodynamic and
Beam Equilibrium and Stability

R. Betti and E. Strait – Co-Chairs

Wave and Particle Interactions

D. Batchelor and W. Kruer – Co-Chairs

Plasma Boundaries and Interfaces

G. Porter and B. Lipshultz – Co-Chairs

# Common Themes Among Sub-groups

- Need additional and improved comparisons between experiment, simulations, and theory
- Need for advances in diagnostics and visualization
- Utilization of tera-scale computers and modern computational techniques
- Connections to non-fusion applications
  - Plasma materials processing
  - Space/astrophysics
  - Accelerators
  - Basic physics
- Devote a portion of the budget to enhance interaction with scientists working in related disciplines

# Turbulence and Transport Science Subgroup

Organizers: Greg Hammett, Paul Terry, Bruce Cohen, John De Groot, Martin Greenwald, Arnold Kritz, Ed Synakowski, Richard Town

Overview talks: E. Synakowski, J. Drake, W. Kruer, J.P. Matte, S. Glenzer

Contributed talks: Glenn Bateman, Juan Fernandez, Paul Terry, Bill Tang, Max Tabak, Mike Key, Jim Hammer, George Morales, Stuart Zweben, Amiya Sen, Leonid Zhakharov, Stan Luckhardt, Greg Hammett, Scott Parker, Jim Callen, Wally Manheimer, and David Newman.

# Turbulence and Transport Science Goals

1. Pursue the challenging, yet realistic goal of developing comprehensive predictive transport models, based on physically reasonable assumptions and well-tested against experiments
2. Develop tools and understanding for control of transport and transport barriers
3. Improved IFE heat transport models and better understanding of fast ignitor physics

MFE and IFE share similar techniques – details differ

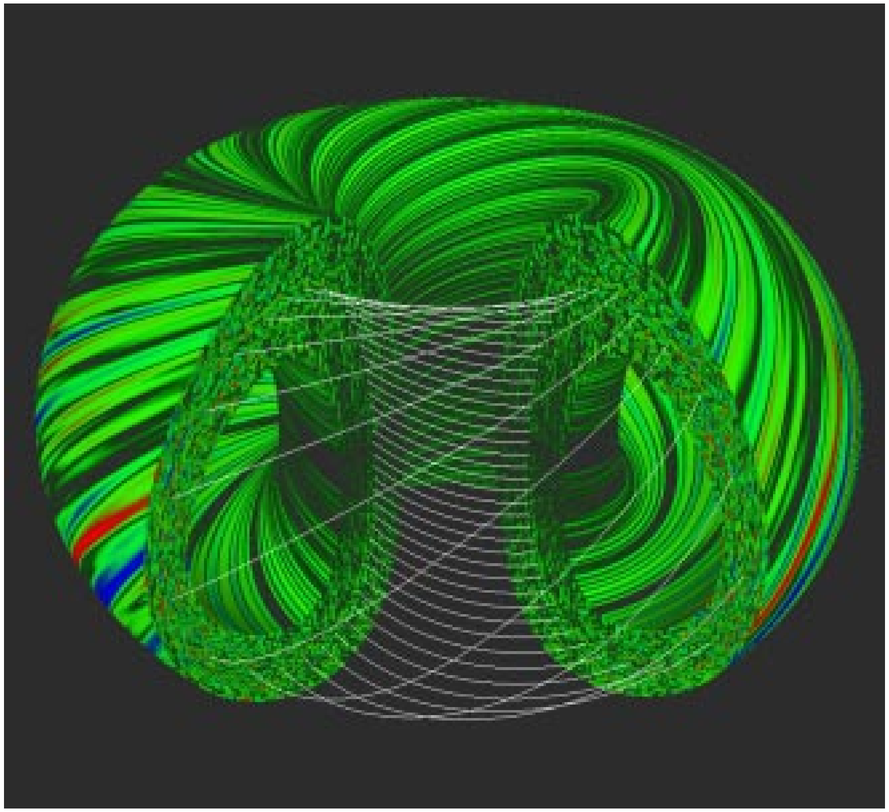
# Transport Goals: Important and Feasible

- MFE Performance is sensitive to transport
  - Increasing confinement time (relative to L-mode) by 30% causes Q to rise from Q = 5 to ignition
  - Need to go beyond empirical extrapolations. Comprehensive transport simulations and improved basic scientific understanding will improve design confidence & enhance scientific credibility
- AT designs reduce COE by ≈ 40% with H x 1.5 and $\beta_n \times 2$
  - Experiments have suppressed turbulence and achieved confinement needed for AT
  - Uncertainties remain regarding scaling AT to larger reactor-scales. Simulations and improved understanding could help resolve
- Computer power increases by one-hundred fold 10 years
  This combined with advances in physics understanding and algorithms, makes fairly realistic and complete simulations feasible
- Potential spinoffs: turbulent transport in astrophysical plasmas, nonlinear dynamics, ...

# Goal 1: Comprehensive transport models

- Pursue the challenging, yet realistic goal of developing comprehensive predictive transport models, based on physically reasonable assumptions and well-tested against experiments

- Several models reproduce core T(r) with 15-30% RMS accuracy in some regimes. More comprehensive simulations needed for a wider variety of regimes and more accuracy.
- Relatively complete simulations are becoming feasible (with non-adiabatic electrons, electromagnetic fluctuations, realistic geometry, edge recycling ...).



Numerical Tokamak Turbulence Project

# Goal 1b: Detailed Experiment/Theory Comparisons

- Advances in simulations and diagnostics are enabling more detailed comparisons that give insight into turbulent processes.
  - not just T(r), but also T(r,t) heat-pulse perturbations, transport barrier dynamics.
- Study turbulence causal links more directly & quantitatively:
  - Improved utilization of existing diagnostics: k & $\omega$ spectra, cross-correlations, bi-spectra, … in systematic parameter scans. Require dedicated experimental time.
  - Develop novel fluctuation/imaging diagnostics.
- Improve understanding of complex codes by theoretical analysis of simplified models and codes that isolate key physics. Understanding underlying basic physics crucial to successful & credible transport modeling.
- Test on existing innovative-concept experiments, and eventually use to predict and optimize future innovative-concept and next-step experiments.

# Goal 2: Controlling Transport Barriers

- Develop tools and understanding for control of transport barriers
  - scaling to larger reactor-scale experiments (requirements for $E \times B$ shear, power thresholds, electron transport)
  - how to make transport barriers steady state by controlling them to avoid $\beta$ limits . . .
- Edge transport barriers need better understanding
  scaling of H-mode power threshold, edge pedestal scaling, density limit, ELM energy burst
- Explore control
  via localized heating and via sheared flows from IBW and other RF, low-energy beams, anomalous flows, pellets, liquid walls. . .
- Local pressure profile control
  high leverage for enabling high $\beta$ AT designs and reducing COE, also relevant to ST, stellarator, RFP. . .
- Nonlinear dynamics of transport barriers and turbulence suppression
  intrinsically interesting and exciting: connect with wider scientific community

# Goal 3a: Improved IFE Heat Transport Models

- Current indirect drive experiments adequately modeled
  - with flux-limited transport and self-generated **B** fields
- IFE hohlraums may have higher temperatures
  - Non-local transport will be more important
- Direct drive more sensitive to hot electron thermal transport
  - improved heat transport modeling will increase confidence in achieving laser-driven IFE
  - Quantitative comparisons of simulations and experiments needed to evaluate transport models
  - Need improved 2-D and 3-D transport models to be integrated into IFE design codes

# Goal 3b: IFE Fast Ignition Physics

New physics issues include:

- Interaction of ultra-intense laser pulses with plasmas
  - propagation of laser pulse through under-dense plasma
- Propagation of relativistic charged particles
  - transport in the presence of self-generated magnetic fields and return currents in over-dense plasmas
- Need better diagnostics and computational models
  - for ultra-intense laser-plasma interactions

# Magneto/Hydrodynamic and Beam Equilibrium and Stability Subgroup

Co-Chairs: R. Betti and E. Strait

Organizers:

J. Callen, J. Cary, A. Friedman, S. Lund, J. Manickam, M. Rosen, H. Strauss

Speakers:

A. Reiman, R. Davidson, R. Town, R. Bangerter, G. Navratil, J. Freidberg, J. Lindl, J. Manickam, J. Finn, H. Strauss, J. Dahlburg, R. Nebel, S. Lund, T. Hayashi, R. La Haye, S. Prager, M. Rosen, L. Steinhauer, J.-N. LeBoeuf, S. Cohen, M. Yamada, H. Ji, P. Bellan

# Goals of the M/HD-Beams subgroup

- Identify critical issues of equilibrium and stability in fusion energy science, and outline research activities to address these issues in the next decade.
- Focus on MHD, hydrodynamic, and beam sciences that underlie the magnetic confinement, inertial target, and heavy-ion driver approaches to fusion.
- Emphasize scientific understanding and comparison of theory, modeling, and experiment.
- Consider MHD, hydro, and beam topics within the following areas:
  - 3D equilibrium
  - Stability
  - Resistive MHD and magnetic field generation

# MHD Plasma Science for MFE

Issue: Ideal and resistive MHD have been very successful, but …..

**Present understanding of MHD is not sufficient to describe some important macroscopic behavior.** (neoclassical tearing, resistive wall modes, relaxation phenomena, energetic particle instabilities,…)

- Challenge: Extended MHD models (flow, 2-fluid, ρ*, kinetic effects, …)
  - Opportunity: Further develop and apply 3D nonlinear codes
  - Opportunity: Explore models for inclusion of non-standard MHD effects
- Challenge: Improved analytic theory and computational methods to understand self-consistent systems with mixed chaotic and integrable regions
  - Opportunity: Further develop and apply 3D equilibrium codes
  - Opportunity: Develop and apply self-consistent Hamiltonian dynamics

➨ Improved MHD models can benefit other branches of plasma science.

# MHD Plasma Science for MFE (cont'd.)

- Challenge: More complete experimental information for comparison with theory and modeling
  - Opportunity: Develop diagnostics for 2D and 3D imaging of MHD instabilities
  - Opportunity: Develop high resolution diagnostics for transport barriers
- Challenge: Improved physics understanding of new approaches to improving MHD stability, through theory, modeling, and experiment
  - Opportunity: Further explore configurational stabilization
    - 2D and 3D shaping, profile control, rotation
  - Opportunity: Develop feedback stabilization of MHD modes
    - Localized current drive, external coils

# IFE Target Issues

- Rayleigh-Taylor Instability Opportunities

**Direct Drive:** Pursue improving ablative stabilization, while maintaining low adiabat for high gain ($\propto 1/$ adiabat)

**Direct and Indirect Drive:**

- Full sphere 3-D multi-mode hydro simulations
- "shorter, faster, colder" and convergent geometry measurements
- explore non-local in space, non-Local Thermodynamic Equilibrium, **B** fields, . . . in hydro codes

**Z-pinch** Develop imaging diagnostics and 3-D simulations and mitigation schemes to further improve X-ray emission

- Laser-Plasma Coupling

**Indirect Drive:** Instability saturation levels and their scaling with the effect of laser-induced **B** field

**Fast Ignitor** Relativistic e-beams and **B** fields set performance

**Opportunities** Included **B** field effects by integrating micro-physics into hydro codes and benchmarking with experiments

# Heavy Ion Fusion Driver Beams

- Target requirements set the incident beam requirements
- Beam properties result from the interplay among focusing fields, intense space charge, and beam environment

**Issues** Avoid emittance growth and halo generation from

- intense space charge effects
- instabilities in driver and chamber
- machine imperfections

Other real-world effects: stray electrons, chamber processes, ...

**Challenge** Details of beam distribution are important
Need kinetic description, phase-space diagnostics

**Opportunities**

- Self-consistent source-to-target simulations becoming practical
- Use PIC, $\delta f$, Vlasov, kinetic/fluid hybrid, hierarchy of detail
- New high-current experiments provide critical tests

# Plasma science – Wave Particle Interaction Subgroup

**D. B. Batchelor, W. Kruer – Chair**

**Organizing committee: D. B. Batchelor, W. Kruer, R. Nazikian, C. K. Phillips, M. Tabak**

**Breakout groups:**

**Injected waves: D.B. Batchelor, C. K. Phillips – coordinators**

**M. Porkolab, J. Hosea, V. Chan, D. Rasmussen – discussion leaders**

**Plasma generated waves: R. Nazikian – coordinator**

**H. Burk, W. Heidbrink, R. Nazikian – discussion leaders**

**IFE: W. Kruer – coordinator**

# 5 to 10 year goal: Develop reliable RF plasma control for successful experiments, leading to attractive reactors

**Plasma Processes:**

Transport

Turbulence

MHD stability

$\alpha$ heating

⟺

**Plasma Parameters:**

Pressure profiles
$n_j(r)$, $T_j(r)$

$q(r)$ profile

flow profiles
$v_\theta(r)$, $v_\phi(r)$

$E_r$ profile

⟺

**RF control mechanisms:**

Localized heating

Localized Current Drive

Driven plasma flows

Driven radial fluxes

Distribution function modifications

- **Success of any magnetic fusion concept will likely depend on controlling these non-linearly coupled processes**
- **Some RF techniques are developed and used routinely in tokamaks, but have only scratched the surface for other concepts and other techniques**
- **Key is understanding RF physics and developing accurate predictive capability**

# Research program – To realize this potential we must:

- Support ongoing research in application of advanced RF techniques to tokamaks. Address the special needs of non-tokamak devices

- Improve the reliability, compatibility and flexibility of couplers by understanding the physics of antenna/plasma interaction, and supporting innovative launcher development

- Understand the coupling problems of Ion Bernstein Waves (IBW) and develop the science and technology necessary to make it work reliably

- Support development of innovative wave physics approaches. – high harmonic fast wave, fast wave/Ion Bernstein Wave mode conversion, electron Bernstein wave, low $v_{phase}$ Current drive, buckets, $\alpha$ channeling
  - Experiment, theory and modeling
  - Launcher development
  - Advanced wave diagnostics

# Wave Physics Introduced by Energetic Particles

- **Energetic particles introduce additional instabilities**
  A. "Universal" drive leads to possible instability in burning plasma if drift frequency is larger than the wave frequency -- $\omega^*$(alpha)>$\omega$(wave)
  B. As $\omega^*$(alpha)≈200 $\omega^*$(thermal), otherwise stable plasma modes can be destabilized, e.g., Alfvénic waves
  C. Linear waves have been observed as predicted by theory
  D. New modes identified that grow on the energetic particles

- **Non-linear evolution and transport**
  A. Wide variety of non-linear phenomena observed; bifurcations, frequency chirping, avalanches, convective losses etc.
  B. Considerable analytic and numerical progress in describing above data
  C. Need to develop comprehensive predictive understanding of spontaneous wave-particle phenomena using fully non-linear kinetic-MHD codes coupled to experimental data and analytic interpretation
  D. These numerical techniques for describing energetic particle phenomena can be generalized to a complete kinetic description of plasmas ranging from Tokamaks to Field Reverse Configurations

# Challenges and Opportunities for Phase Space "Engineering" of Energetic Particles

- External wave control of energetic particles has the potential to control power flow in a reactor
  A. Strong interaction of energetic particles with external waves observed
  B. May be used for current drive, pressure and momentum profile control
  C. Possible enhancement of fusion power density (alpha channeling)
  D. Actual methods of control require development

- Near term opportunities include
  A. Laboratory experiments with detailed measurement of RF waves and particles which can address generic kinetic wave-particle issues
  B. Credible, experimentally validated models need to be developed with the most advanced computational and analytical techniques

- Progress can have significant implications for plasma control

# Cross–cutting issues

- **Connections between wave/particle issues in MFE and IFE**
  - **Wave versus plasma-evolution time scale separation**
  - **2D/3D issues**
  - **Need for tera-scale computing**

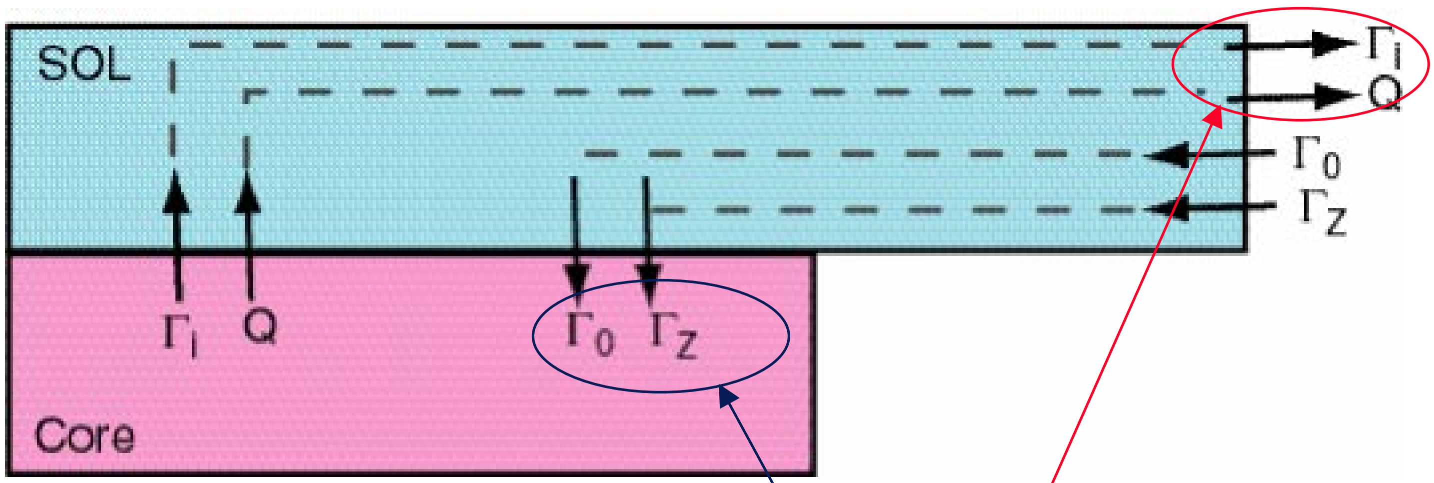
**Establish MFE/IFE collaborations on similar issues:**

- **non-linear plasma instabilities driven by intense electomagnetic waves (e.g., ponderomotive effects in laser fusion ⇔ Ion Bernstein Wave launchers)**
- **Diagnostics (e.g., spectroscopy, ...)**

# Boundary Science Issues

Organizers: G. D. Porter, B. Lipschultz, J. Albritton, R. Cohen, S. Krashinennikov, A. Leonard, M. A. Mahdavi, P. Mioduczewski, T. Rognlien, M. Ulrickson

# Boundary science is used to control plasma/neutral flows




- Improper treatment of the effluxes is hazardous to the health of internal components
- Improper treatment of the influxes is hazardous to the health of the core plasma

# Boundary Science Must Integrate Multiple Physics Disciplines

- Transport physics
  - parallel and perpendicular to **B** field
- Plasma neutral interaction
  - Ionization, charge exchange, and neutral transport
- Atomic physics
  - Radiation, excitation, and recombination
- Plasma-material interaction
  - Sputtering, redeposition, and recycling

# Significant Progress in Understanding Boundary Science

- Diagnostics now provide 2-D plasma profiles
- Thermal loads have been reduced and flows to core adequately controlled in experiments
- Comprehensive 2-D codes are consistent with experiment
  - can produce viable divertor designs for standard tokamak operation

# Needs Identified for Viable Divertor Design for Future MFE Configurations

- Transport Physics
  - Develop physics based perpendicular transport rates and experimental scalings
  - Improve modeling of kinetic effects
  - Include effect of drifts in plasma flow models
  - Improve neutral transport models and validate with enhanced neutral diagnostics
- Expand geometric capability to permit design of 3-D structures (Stellarator, . . . )

# Future Needs (Continued)

- Broader treatment of integration issues
  - Self-consistent coupled core/edge simulation capability
  - Better treatment of plasma-material interaction for materials not yet considered (including liquid walls) and better diagnosis of impurity sources
- Develop active boundary control schemes viable for new plasma regimes

# Cross-cutting Issues

- Fusion plasma physics provides a common framework for discussion of issues and opportunities
  - The four topical subgroups have significant overlap
  - MFE, IFE, and other plasma research have basic plasma physics in common
- Several common themes emerged among the MFE and IFE discussions
  - Need for improved experimental diagnostics
  - Macro/micro integration
  - Taking full advantage of tera-scale computers and modern computational methods

# Fundamental Plasma Science

- Consensus: Need to increase basic plasma research
  - Cannot predict science needed in field with goals 10 years away
  - Other communities have adopted this strategy
  - Achieve higher visibility and recognition
- Scientific communities gain influence as they produce broadly applicable scientific ideas
  - We are judged by how our ideas are used in other fields
- Strongly endorse continuation and expansion of Young Investigator awards, DOE/NSF plasma science awards, plasma science graduate and undergraduate fellowships
  - Needed to attract and keep young scientists and to excite the interest and respect of rest of the physics community