

# **EXTENDED MHD SIMULATIONS: VISION AND STATUS**

**D. D. Schnack  
and  
the NIMROD and M3D Teams**

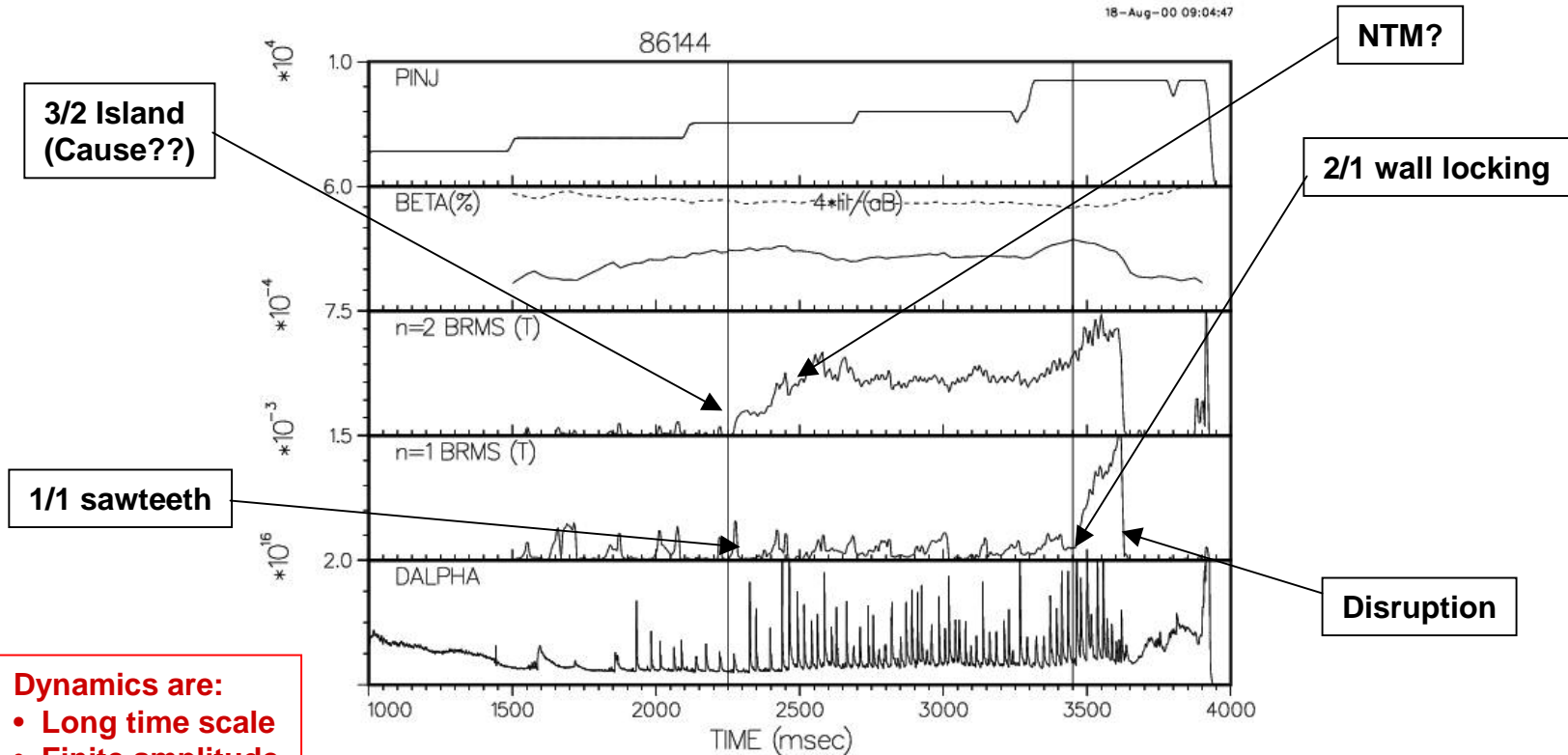
*Center for Extended Magnetohydrodynamic Modeling  
PSACI/SciDAC*



# MODERN TOKAMAKS ARE RICH IN MHD ACTIVITY

Example: DIII-D shot 86144

18-Aug-00 09:04:47



Dynamics are:

- Long time scale
- Finite amplitude
- Electromagnetic
- 3-D

- What is special about 2250 msec?
- What is the nature of the initial 3/2 island?
- Can this behavior be understood?
- Can this behavior be predicted?



# IMPORTANCE OF PREDICTIVE MODELING

---

- Cost of next generation of fusion experiments estimated to be at least several billion \$\$
- Cost proportional to volume:  $\$ \sim V$
- Power density proportional to square of max. pressure:  
 $P/V \sim p_{\max}^2$ 
  - $\Rightarrow \$ \sim 1/p_{\max}^2$  for fixed  $P$  and  $B$  (engineering constraints)
- Physics uncertainties limit max. pressure to  $\sim 2/3$  theoretical  $p_{\max}$ 

***Uncertainties in nonlinear physics account for  $\sim 1/2$  the cost of advanced fusion experiment!***
- Predictive fluid modeling with realistic parameters has high leverage to remove this uncertainty



# MODELING REQUIREMENTS

---

- **Slow evolution\*\***  
**Nonlinear, multidimensional, electromagnetic fluid model required**
- **Plasma shaping**  
**Realistic geometry required**
- **High temperature**  
**Realistic  $S$  required**
- **Low collisionality\*\***  
**Extensions to resistive MHD required**
- **Strong magnetic field**  
**Highly anisotropic transport required**
- **Resistive wall**  
**Non-ideal boundary conditions required**

**\*\* *Integrated modeling required***



# INTEGRATED MODELING IS REQUIRED

---

- ***Non-local kinetic physics affects long time scale evolution***
  - Transport coefficients
  - Neo-classical effects (bootstrap current, NTMs)
  - Energetic particles (TAEs)
- ***Long time scale profile evolution is affected by MHD physics***
  - Relaxation of profiles
  - Profiles affect kinetic physics
- ***Fluid model only computationally practical approach***
  - Multi-dimensional, electromagnetic
- ***Effects of kinetic (sub grid scale) physics must be synthesized into MHD models\*\****
  - Extensions to Ohm's law (2-fluid models)
  - Subcycling/code coupling
  - Theoretical models (closures), possibly heuristic
- ***Effects of MHD must be synthesized into transport models***
- ***Predictions must be validated with experimental data***

***\*\* For Alfvénic and tearing mode time scales, this is called  
Extended MHD***



# INTEGRATED MODELING HAS 3 COMPONENTS

---

- ***Algorithm and code development***
  - Time integration methods for problems with extreme separation of time scales
  - Spatial representation
    - Simultaneously describe large and small scales
    - Extreme anisotropy
- ***Theoretical model development***
  - Closures to fluid equations
  - Synthesis of results from sub grid scale computations into analytic or heuristic models
  - Tightly coupled with computational effort
- ***Model validation***
  - Validation of algorithms
  - Calibration of models with data

*All 3 components must be enabled for an effective program*



# I. ALGORITHM AND CODE DEVELOPMENT

---

- ***Fusion MHD-like problems are among the most challenging in computational physics***
  - Extreme separation of time and spatial scales (large  $S$ )
  - Extreme anisotropy
- ***Need to develop, test and deploy algorithms appropriate for these problems***
  - Implicit methods, non-cartesian grids, FFTs
  - Methods appropriate for strong flows, low density regions

***Is there a better way?***
- ***Boundary conditions***
  - Vacuums, resistive walls, coils, wall stresses, etc.
- ***Code coupling and steering***
  - Efficient integration of disparate models into a single computation
  - Run time decision making



## II. THEORETICAL MODEL DEVELOPMENT

---

- ***We don't know what form of the fluid equations to solve!***
  - Fluid model possibly valid only perpendicular to magnetic field
  - How to incorporate important parallel physics in nearly collisionless regime?
- ***Kinetic, non-local processes affect MHD evolution***
- ***Require computationally tractable forms for these effects***
  - Kinetic effects are non-local
  - Fluid models are local
  - Formulation in configuration space  $(r,t)$ , not Fourier space  $(\omega,k)$
- ***Closures***
  - Analytic expressions based on moments of kinetic equations
  - Synthesis of results from sub grid scale kinetic studies into heuristic models
- ***Subcycling of physics modules***
  - Particle  $(\delta f)$  methods
    - OK for ions (minority species?)
    - Impractical for electrons - analytic or heuristic formulation required



# III. MODEL VALIDATION

---

- ***Validation with experimental data is an essential part of attaining a predictive capability***
  - Algorithms
  - Analytic components
- ***Some requirements for successful validation capability:***
  - Common structure, handling, and analysis for experimental and simulation data
  - Ability to view experimental and simulation data In the same way
  - Ability to transport and store large amounts of 3-D time dependent data
  - Synthetic diagnostics



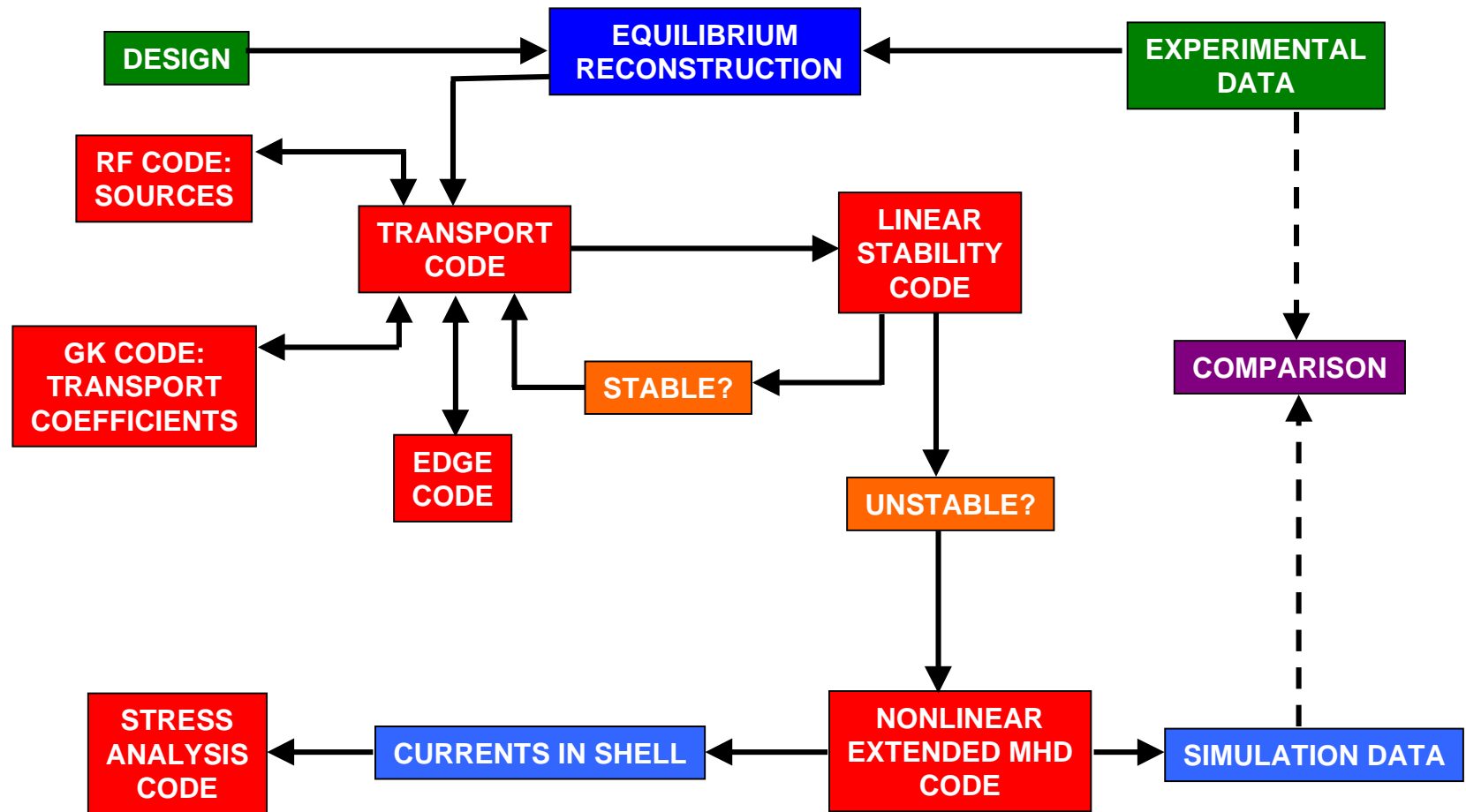
# ENABLING COMPUTER SCIENCE TECHNOLOGIES

---

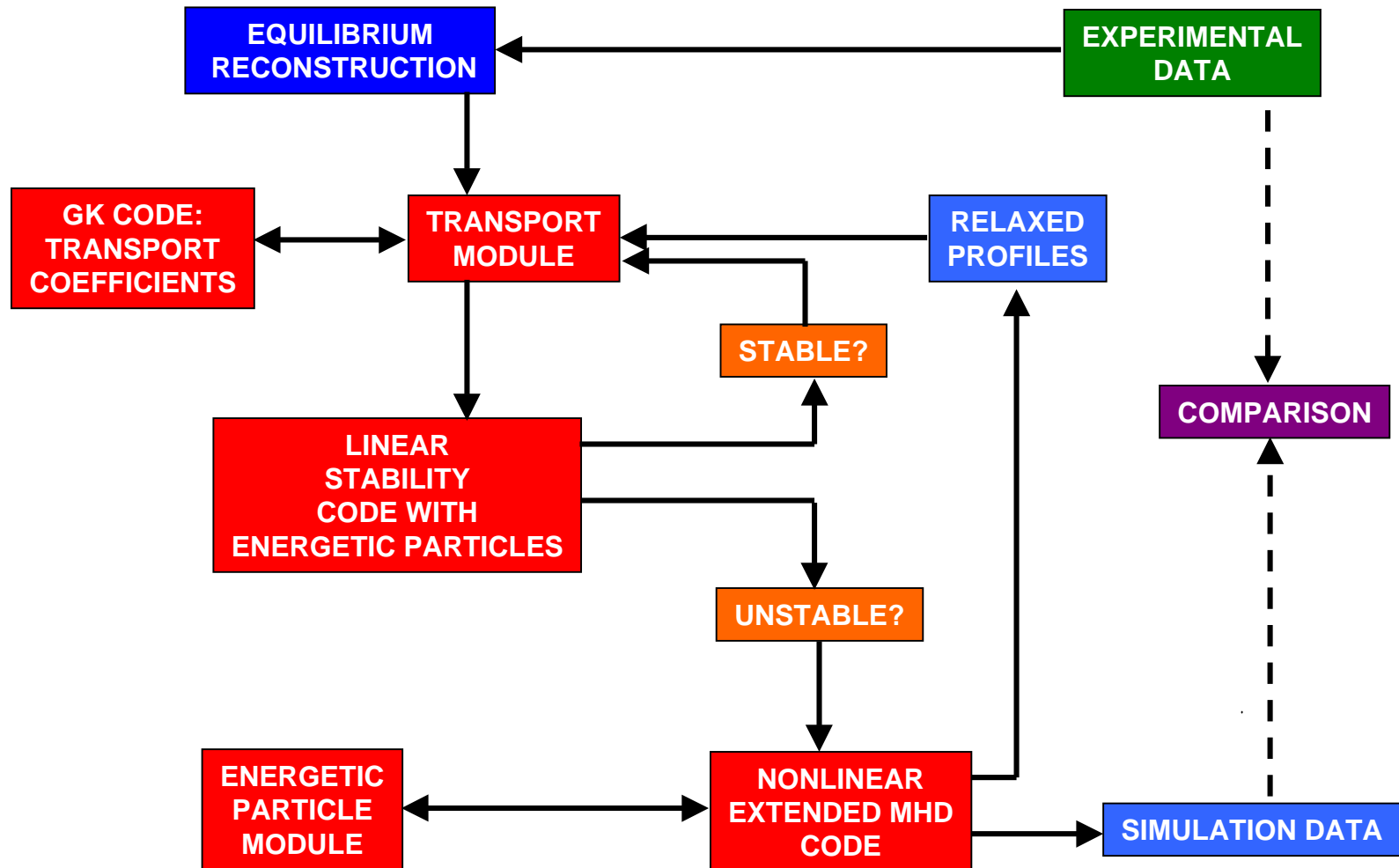
- ***Largest, fastest computers!***
  - But intermediate computational resources often neglected, and...
  - ***The computers will never be large or fast enough!***
- ***Algorithms***
  - Parallel linear algebra
  - Gridding, adaptive and otherwise
- ***Data structure and storage***
  - Adequate storage devices
  - Common treatment of experimental and simulation data
  - Common tools for data analysis
- ***Communication and networking***
  - Fast data transfer between simulation site and storage site
  - Efficient worldwide access to data
  - Collaborative tools
  - Dealing with firewalls
- ***Advanced graphics and animation***



# VISION: VDE EVOLUTION

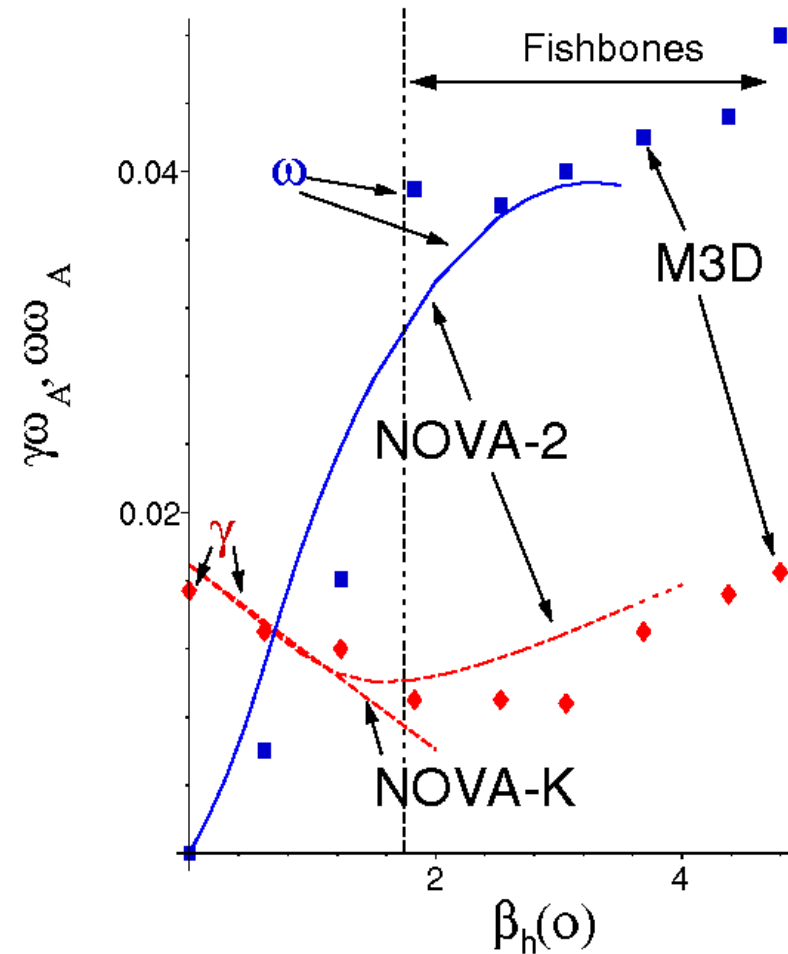


# VISION: SAWTOOTH CYCLE



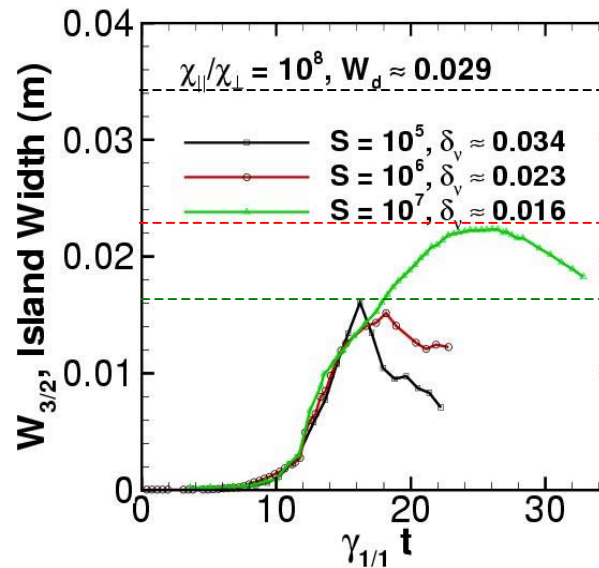
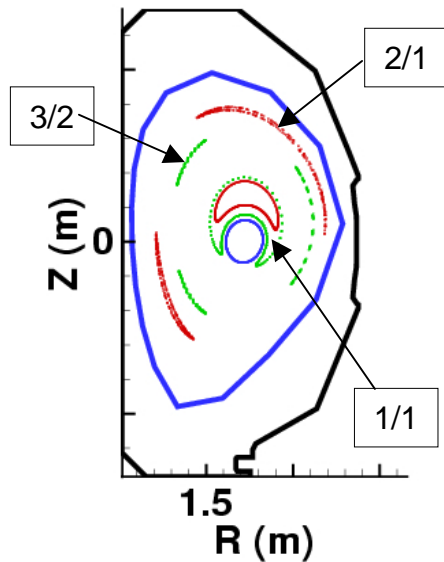
# STATUS: ENERGETIC PARTICLE EFFECTS IN MHD

- Effect of energetic particle population on MHD mode
- Subcycling of energetic particle module within MHD codes
- M3D agrees well with NOVA2 in the linear regime
- Energetic particles are being incorporated into NIMROD
- NIMROD/M3D linear and nonlinear benchmarking expected by APS



# STATUS: NEOCLASSICAL TEARING MODE

DIII-D shot 86144 @ 2250 msec



- Nonlinear simulation with NIMROD code
- Look for 3/2 neoclassical mode driven by 1/1 sawtooth
- Use PFD (analytic) closure
- Threshold island width  $\sim 2$ -4 cm (uncertainty in  $\Delta'$ )
- $W_{3/2} \sim 6$  - 10 cm in experiment
- Still need larger  $S$ , more anisotropy

***Cannot cheat on parameters!***



# SUMMARY

---

- ***Predictive simulation capability has 3 components***
  - Code and algorithm development
  - Tightly coupled theoretical effort
  - Validation of models by comparison with experiment
- ***Fundamental model should be multi-dimensional, nonlinear, electromagnetic, and fluid***
- ***Integration required for:***
  - Coupling algorithms for disparate physical problems
  - Theoretical synthesis of results from different models
  - Efficient communication and data manipulation
- ***Progress is being made with Extended MHD***
  - Integration of energetic ion modules into 3-D MHD
  - Computationally tractable closures
  - Resistive wall modules

***Need to bring a broader range of algorithms and codes to bear for overall fusion problem***

