Fusion Theory Issues for a Burning Plasma Program

Presented on behalf of the

Theory Coordinating Committee

http://web.gat.com/theory/tcc/

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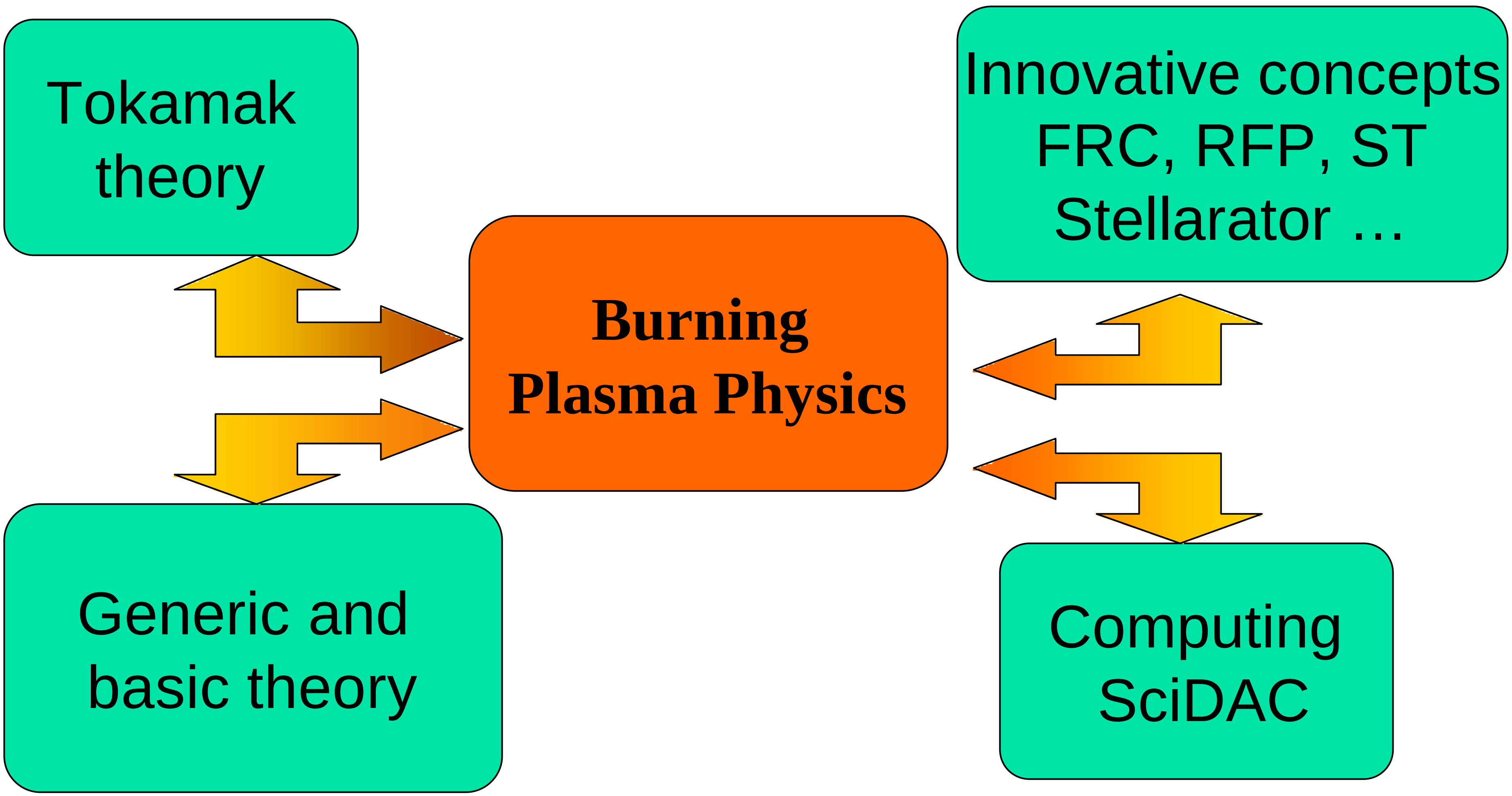
DOE Budget Planning Meeting

Rockville, MD, March 16-17, 2004

Focus of this talk is on a subset of the theory program



The need for improved theoretical modeling is well recognized

National Research Council report on Fusion

- If the U. S. magnetic fusion program is to take full advantage of ITER, it will need to develop a first-principles understanding of the phenomena which determine ITER's performance.
- This requires improved models of the edge plasma, transport barriers, density limits, core confinement and MHD instabilities.
- Reduced descriptions have been useful, but coupling them in disparate regimes is a formidable challenge, eg. Edge physics
- Going forward, the simulation program will need expansion.

National Academy BPAC Report indicates the areas of scientific value – 2003

- Nonlinear behavior of confined plasma with self-heating
- Plasma confinement and stability at large scales
- Self-heating effects on equilibrium and confinement
- Alpha particle effects on equilibrium and confinement
- Operating strategies for energy producing plasmas

Key points

- The national fusion theory program is healthy and active, but lean
- The level of success of a Burning Plasma program will depend on advances in the theory of fusion science
- Progress will depend on advances in analytic physics, computational modeling and comparison of theory with experiment
- All topical areas are not at the same level of maturity. A funding boost can help assure timely progress.

Burning plasma physics modeling challenges and needs

- Modeling approaches
  - Analytic theory
    - Improved fluid and kinetic equations
    - Analytic models of phenomena
  - Micro- and macro-stability codes (multi-fluid; kinetic)
- Challenging aspects
  - Multiple space/time scales and collisionalities
  - Complicated geometry
  - Stochasticity – plasma & fields
  - Strong nonlinearities
- Integrated modeling
  - Benchmarking – Theory-*theory* and Theory-Experiment comparison
  - Coupling multiple topical areas
  - Disparate space and time scales

Outline and metric of progress in the context of integrated modeling of a burning plasma

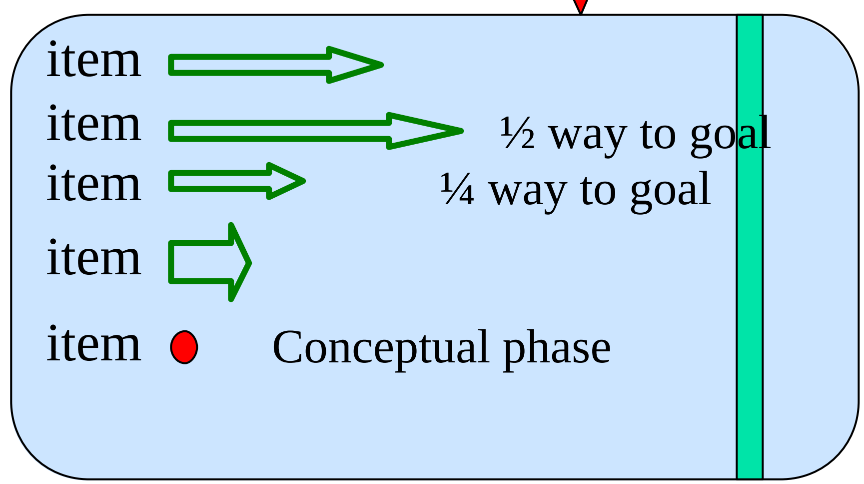
- RF heating and CD
- Edge Physics
- Transport and turbulence
- MHD
- Energetic particle – wave interactions
- Integration

A subjective metric for measuring the status of a topical area :

•Priority of sub-topic **highlighted**

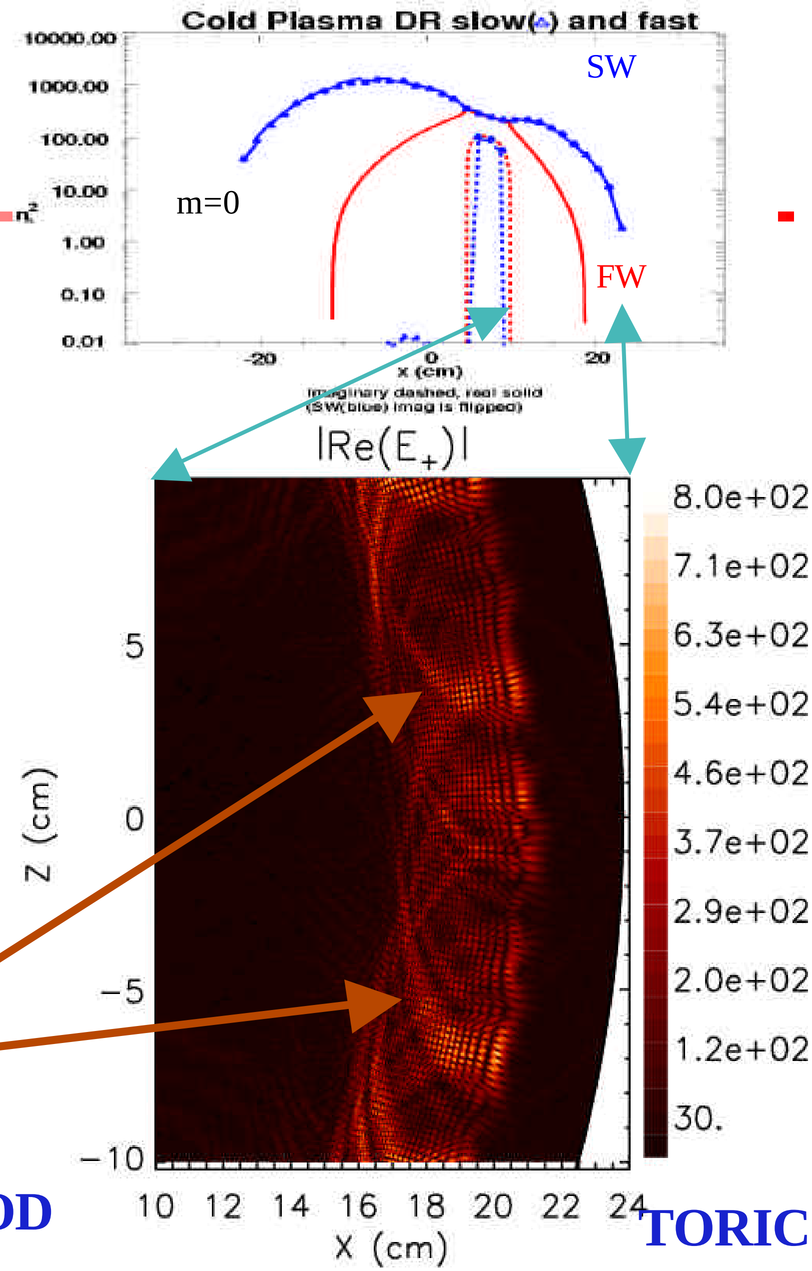
•Level of effort
•Time line
} Not discussed

•Level of progress



RF modeling can follow the 3D wave field propagation and mode conversion

- Process:
  - FW coupled at plasma edge, propagates inward, and converts to slow LHW.
  - Slow LHW propagates out to edge cut-off, reflects inward, and converts back to FW.
  - Process repeats itself until wave power is fully damped.
- LH full-wave field pattern reminiscent of ray tracing results.

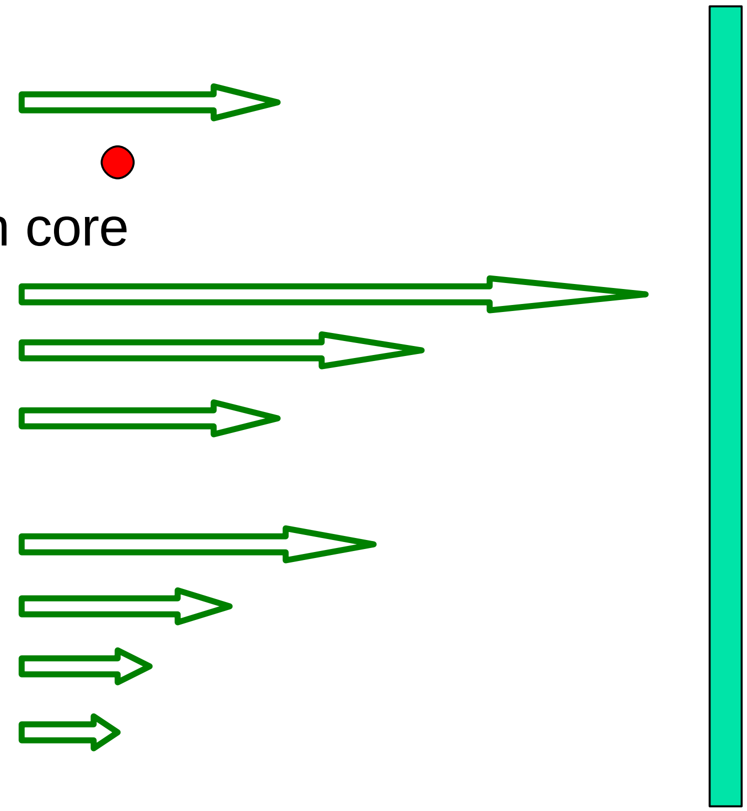


CMOD

TORIC

There is progress in treating full wave physics, but kinetic and non-Maxwellian issues need more work

- Antenna-plasma coupling
  - 3D full field models
  - transient edge conditions – ELMs…
- Wave propagation and absorption in core
  - Ray tracing
  - Full wave treatment
  - Fokker-Planck- Full orbit effects
  - Non-Maxwellian particles
    - beam, electrons, α-particles
  - Self-consistent equilibrium evolution
  - Spatial resolution, Speed
  - Compact wave-field representation

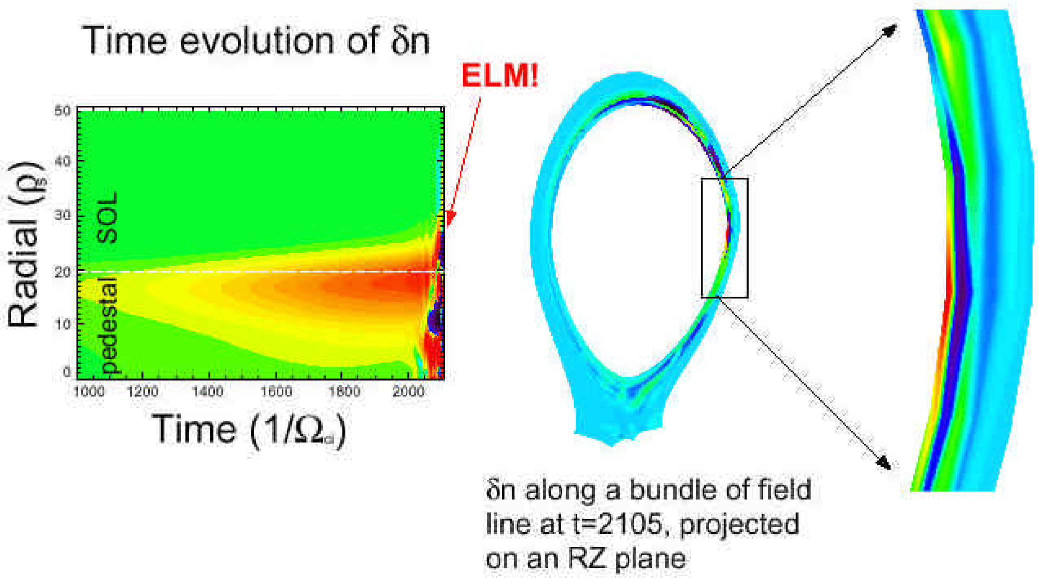


The ability to do integrated modeling of RF physics in a Burning Plasma is limited

- Non-linear closed loop computation with
  - Full-wave solver
  - Fokker-Planck solver
  - Non-Maxwellian plasma response module

  =>Self-consistent RF fields and f(v,r)
- Equilibrium evolution
  - transport, heating and CD
- Effects on MHD stability
  - Sawteeth
  - Neo-classical tearing modes
  - Energetic particle driven modes
- Edge physics

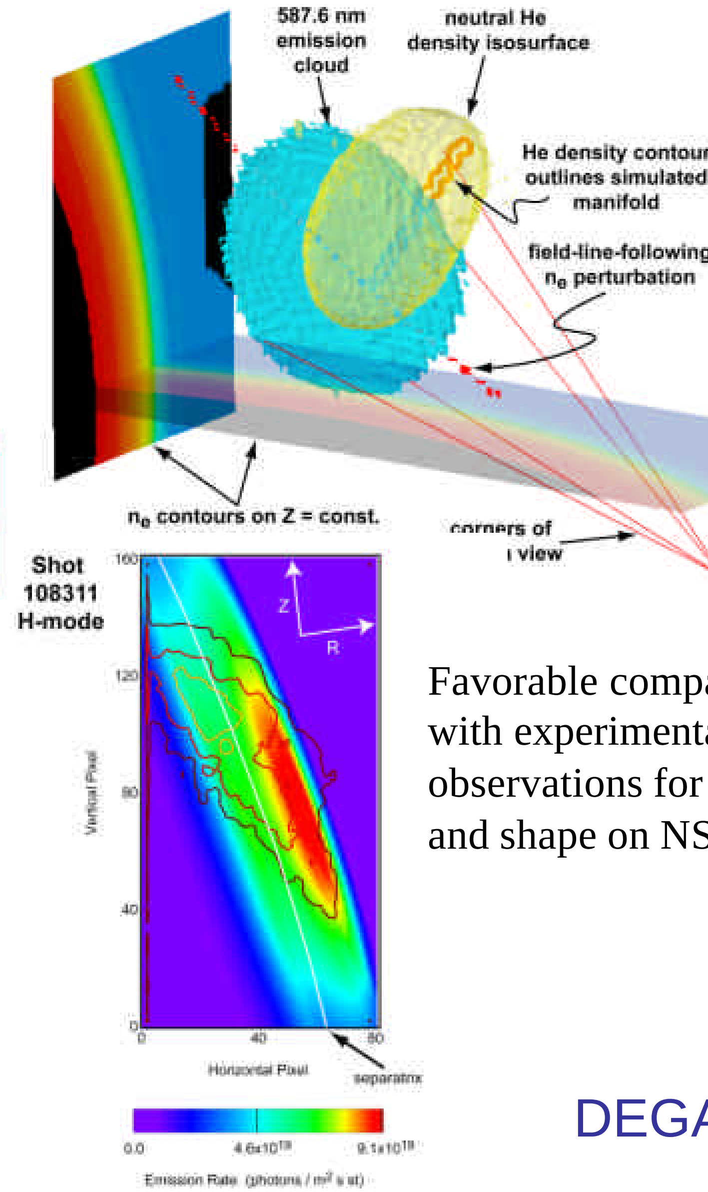
Edge Simulations are coupling MHD events to edge transport



A mode grows on peeling-ballooning time scale and propagates like an ELM

BOUT

3-D Edge Simulations are being compared with experiments



Favorable comparison with experimental observations for size and shape on NSTX

DEGAS 2

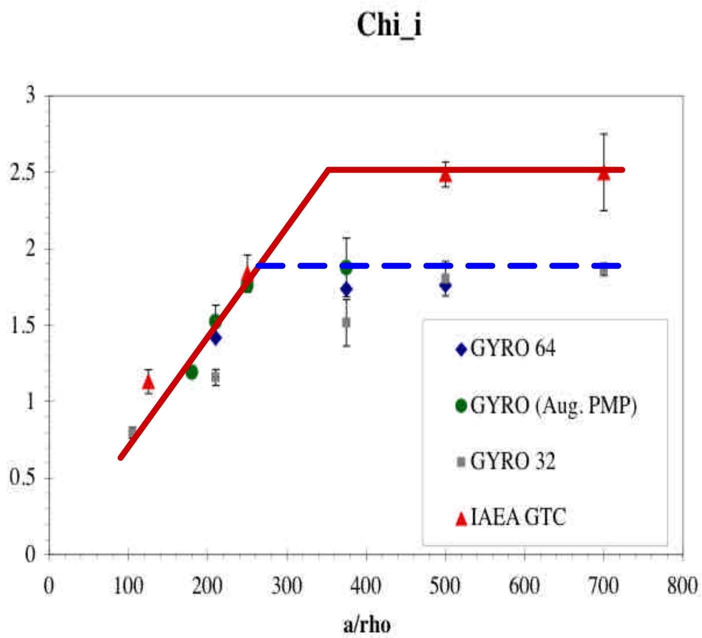
Edge pedestal physics modeling requires advances on many fronts

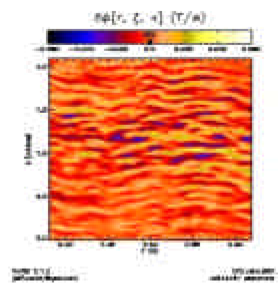
- Pedestal scaling
  - boundary condition for core transport studies - strong dependence of core confinement on pedestal height
- Pedestal physics
  - ELMs
  - Meso-scale transport - blobs
  - L-H transition
  - Density limits
  - Neutrals
  - Edge transport theory
    - - neo-classical, gyro-kinetic
  - Plasma geometry - 3D issues
  - Stochasticity – plasma & fields

Edge physics modeling has to mature significantly to meet the challenge of integrated modeling

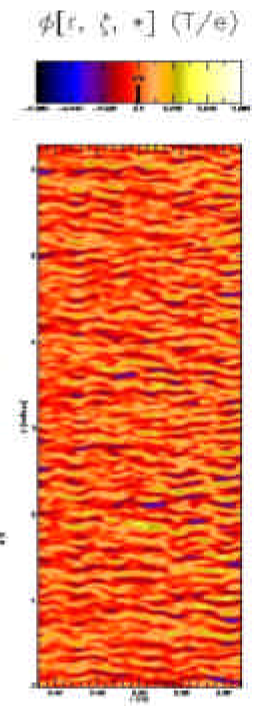
- Plasma wall interaction
  - Neutral hydrogen behavior
  - Impurities - Erosion, transport, & redeposition of wall materials – Tritium retention
  - Dust generation & transport
  - Modeling heat loads
    - Steady
    - Transient – ELMs, disruptions, runaways
- ***Technology funded PSI studies are complementary***
- Integrated modeling challenges
  - Edge turbulent transport with ELMs
  - multiple time, space and collisionality scales
  - non-linear effects in complex 3D geometry
  - Transport – MHD – Particles

Turbulence simulation codes have made significant progress

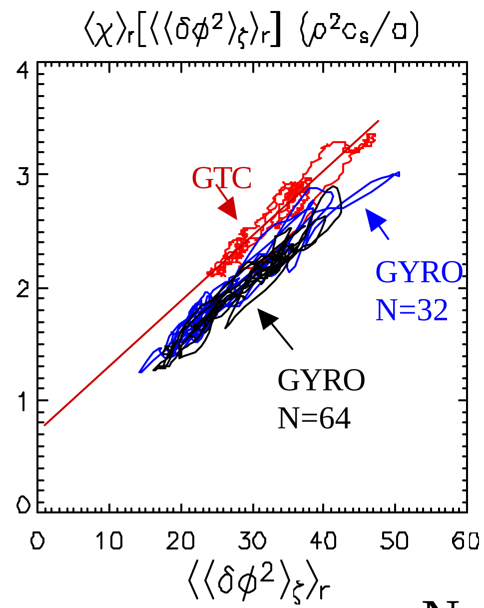




GYRO



GTC



Nevins

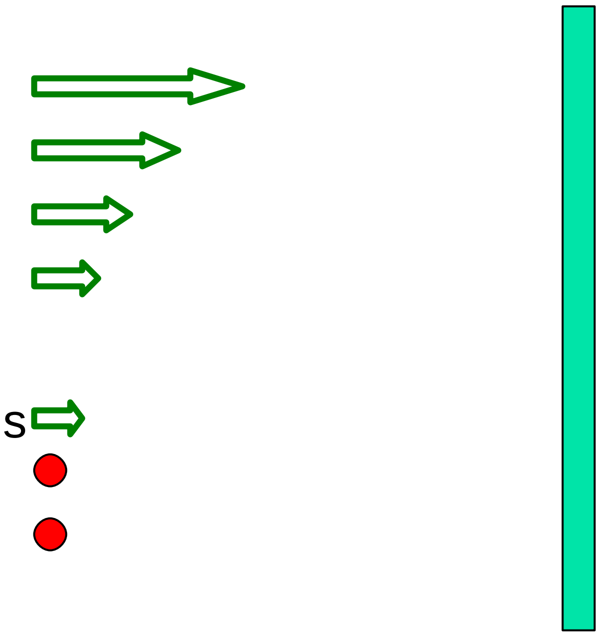
The differences in c_i may be understood in terms of $\acute{a} d f^2 \tilde{n}_z$,
which is observed to depend on the cross-phase between δp and δϕ

Understanding of ion transport is more mature than electron transport

- Basic understanding
  - Model for collisional transport
    - **Neoclassical**
    - paleoclassical, omniclassical (regime dependent)
  - Electron transport: heat and particle
  - Momentum transport
  - ITB formation and ion dynamics
  - Perturbative response
  - Edge dynamics
  - Core profile stiffness
  - Turbulent transport modeling
    - Instability criteria, Estimates for χ
    - Correlation length, Timescales
    - Phenomenology
      - **Zonal flows**, Streamers, avalanches …

Transport simulations are approaching readiness for integrated modeling

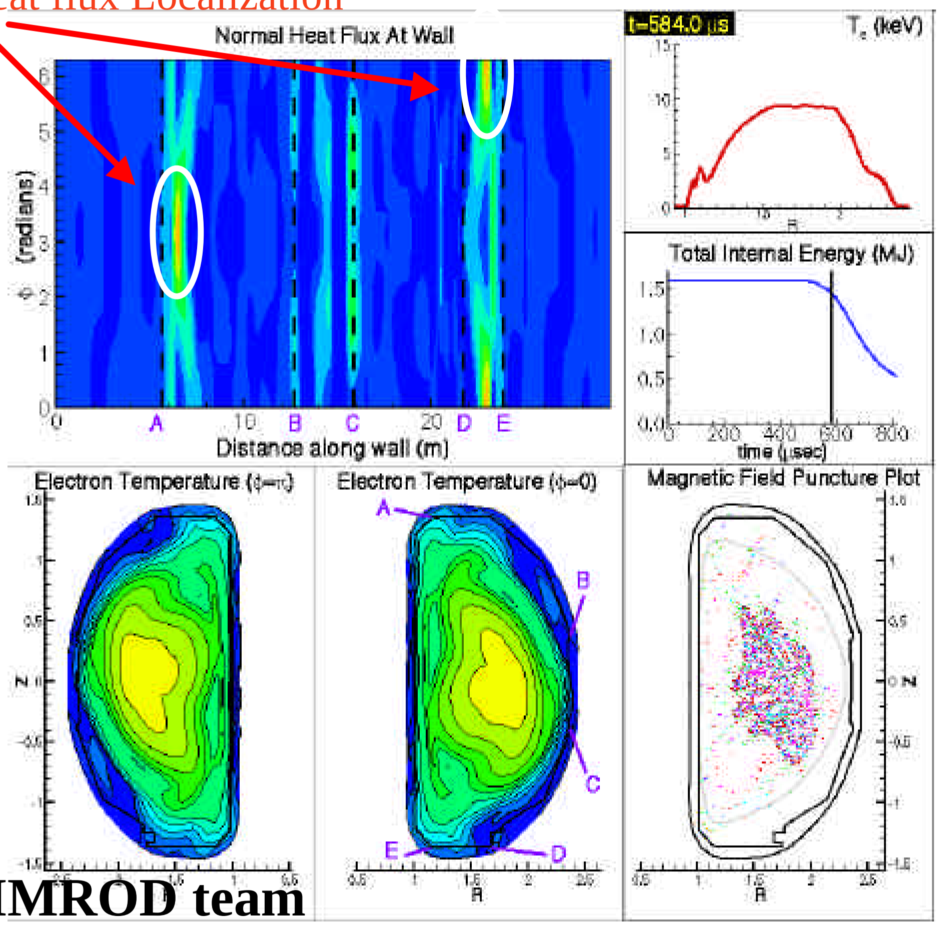
- Global modeling
  - Scaling laws
  - Transition parameters
  - Edge pedestal scaling
  - Geometric effects, κ, δ
- Integration issues
  - Full radius core-edge coupled simulations
  - Coupling to MHD stability
  - Current diffusion time scale



3D MHD simulations are starting to address ITER relevant physics

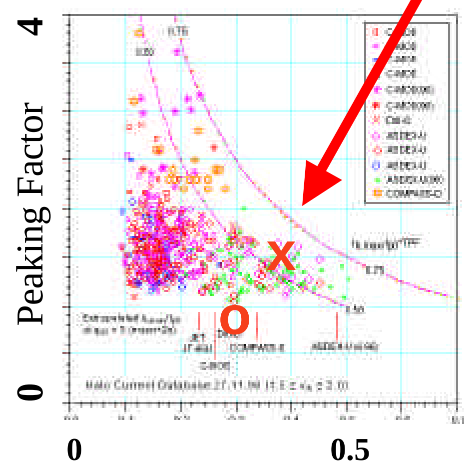
Time-slice of disruption simulation in DIIID

Heat flux Localization



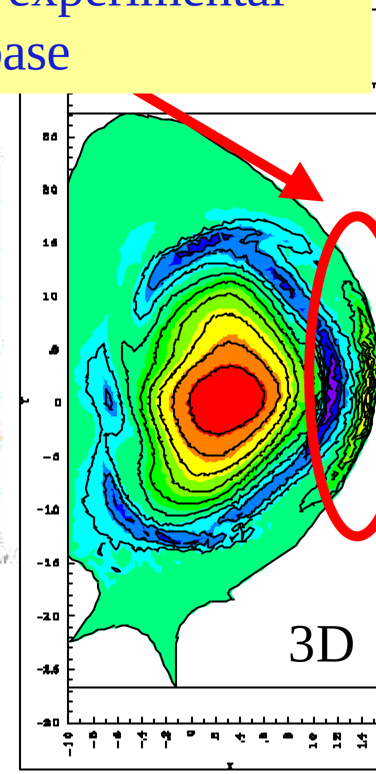
NIMROD team

Halo current characteristics are consistent with experimental database



Normalized halo current

ITER



M3D team

MHD science has made significant progress in modeling a variety of important instabilities

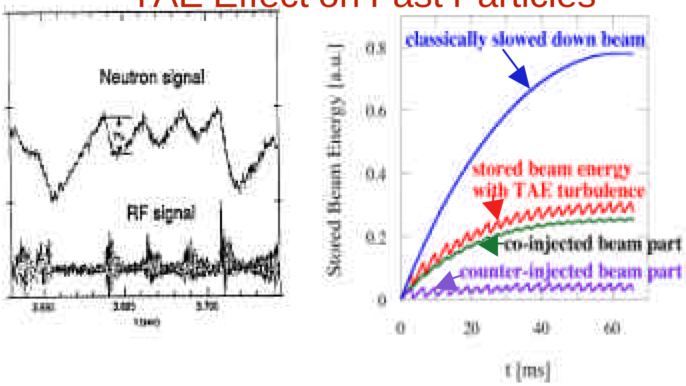
- MHD model advances
  - Realistic parameters,
    - *resistivity, neoclassical viscosity, parallel heat conduction*
  - Kinetic effects
- Sawtooth model
  - Relaxation physics and self-organization
- Physics, Control and mitigation
  - Neoclassical Tearing Modes
  - Resistive Wall Modes
  - Plasma rotation
  - ELMs
  - Error field amplification
- Disruption modeling

Tools are ready for integration of MHD with transport and kinetic effects

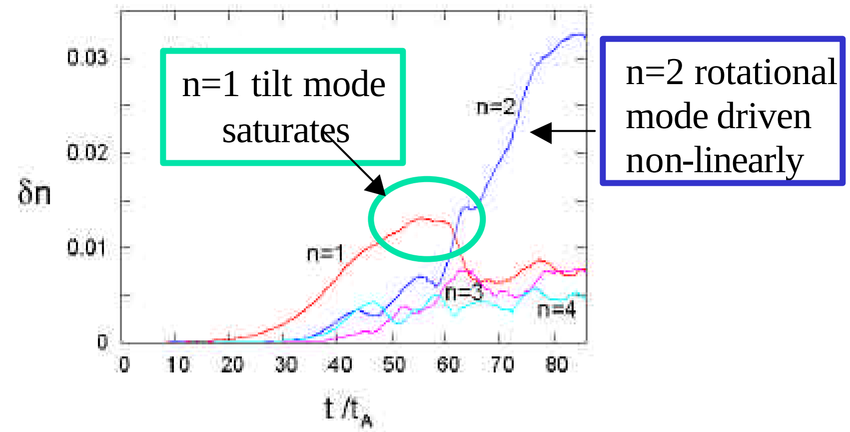
- Extend timescale to transport timescale
- Self-consistent equilibrium evolution
  - Coupling to heating and transport
  - α-particles impact on equilibrium and stability
- Nonlinear evolution of ELMs through multiple cycles
  - Coupling to edge physics
- Role of error fields
  - Resonant field amplification
  - Energetic particle confinement
- Plasma control

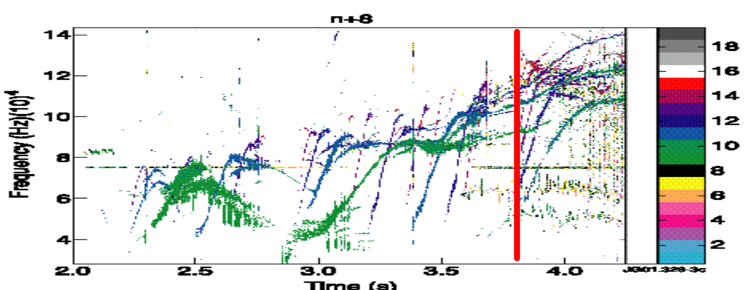
Energetic particle driven MHD studies are maturing

TAE Effect on Fast Particles

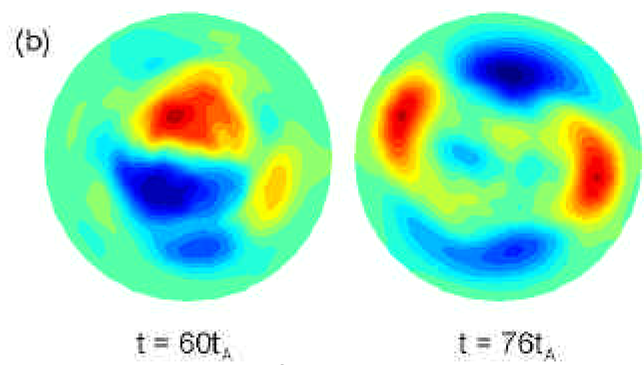


TFTR





IFS/JET



Grand cascades predicted theoretically are used as a diagnostic for q_{min}=m/n

Nonlinear simulations of the tilt instability in an FRC using a hybrid MHD-kinetic code. Advances in hybrid MHD simulations are transferable to other configurations!

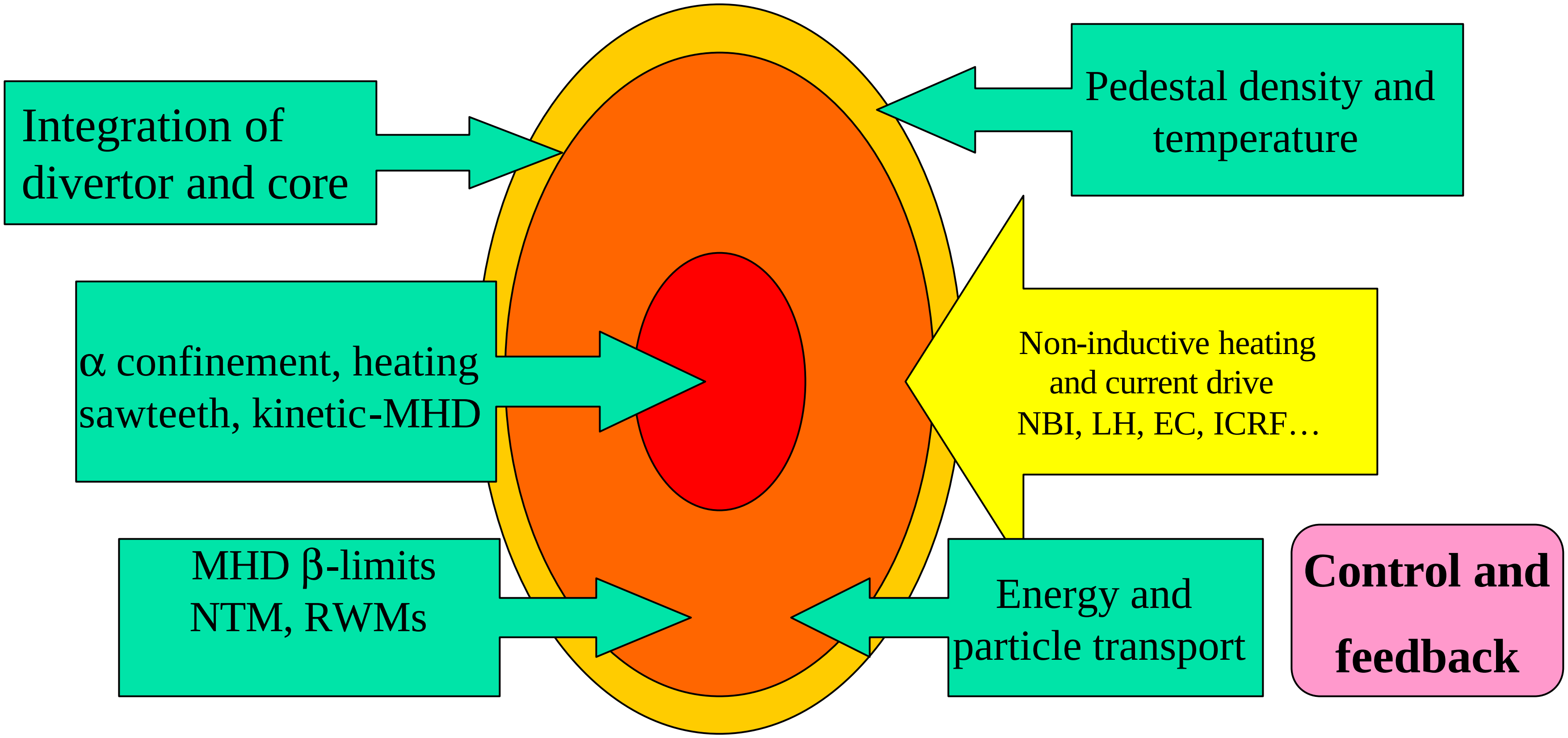
HYM

Need a hybrid model that treats kinetic physics of both thermal and fast particles in a single-fluid framework

- Fast particle physics
  - δF - low-n, high-n :– linear, non-linear, *L*, *NL*
  - Full kinetic treatment of fast particles: F , *L*
  - Gyro-kinetic δF model: *L, NL*
  - Full orbit δF model: *L*
  - Full orbit - Full kinetic – F: *L, NL*
- Thermal particles
  - thermal ions + δF: *L*

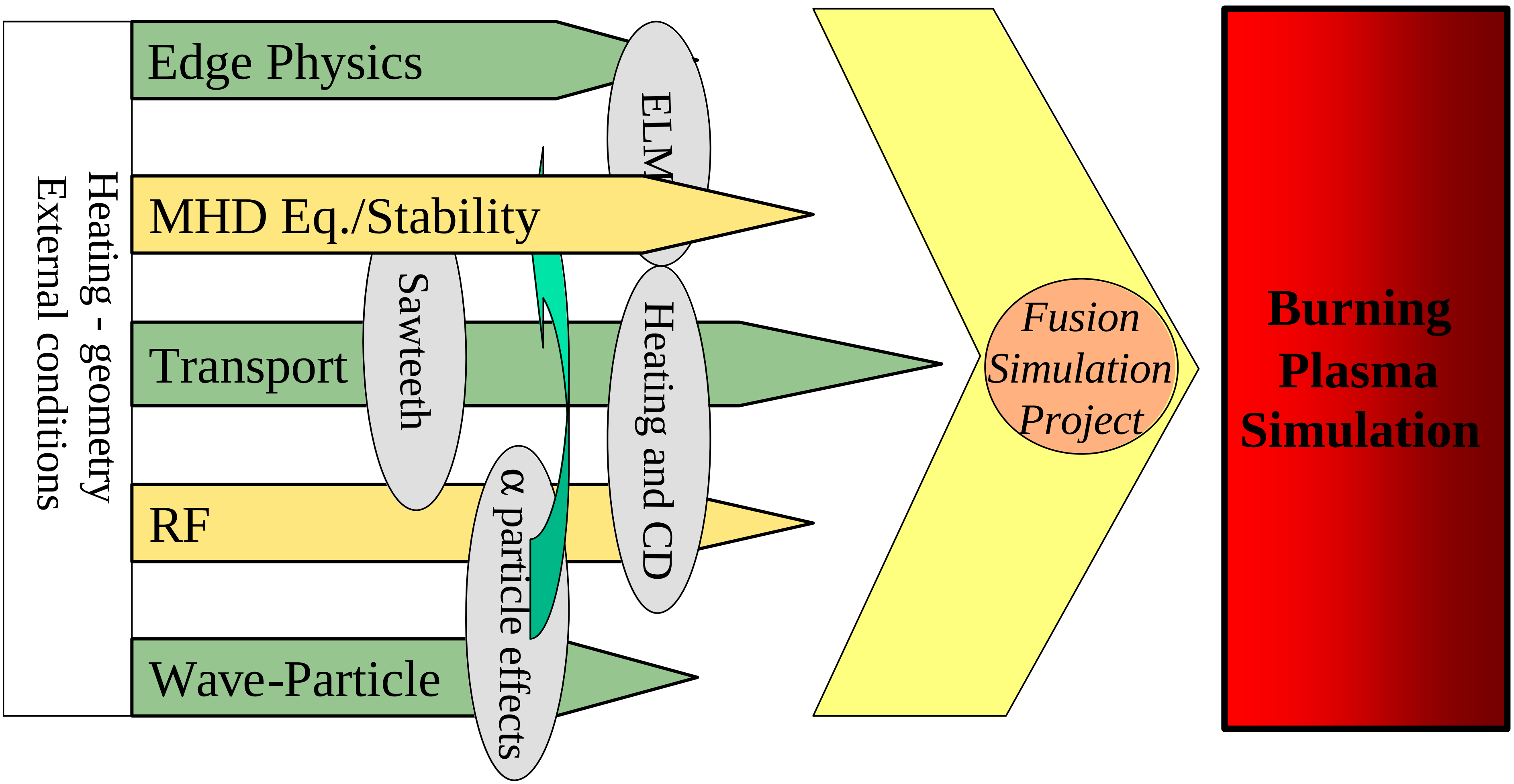
F – full distribution function, *L* – linear, *NL* – nonlinear

Integrated simulation requires reduced models, full simulations and experimental benchmarking



Self-consistent modeling of a nonlinear coupled self-heated system

Fusion Simulation Project could provide the tools for connecting the continuously updated packages for all the topical areas



Budgetary challenges

The theory program has made significant advances in all areas of fusion energy science

- **Meeting the theory support needs for a Burning Plasma program will require more effort**
- **Theory program support is lean – in all areas:**
  basic plasma, tokamak, innovative concepts and computing
- **Need systematic increases to fund all aspects of the program**
- **The demographic challenge:**
  - **Need more entry and mid-level scientists**
  - **Need to pay attention to analytic modeling**