Theory and Simulation Support for Alcator C-Mod

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Outline

• Review plans for theory and simulation support for Alcator C-Mod over the next five years in the following areas:
  – Core transport physics.
  – MHD phenomena – energetic particles and MHD stability
  – Pedestal and Plasma boundary
  – Wave – plasma interactions
  – Integrated scenario modeling

• Point to progress and problems in each area and how they fit into future plans.
Introduction

• Theory and simulation support has several origins:
  – Collaborations with PPPL, UT, IPP (Asdex-Upgrade),
  – Individual initiatives between C-Mod personnel and theorists within MIT (PSFC Theory Group) and outside MIT.
  – Collaborations with SciDAC Centers:
    • Center for Simulation of Wave-Plasma Interactions – (CSWPI)
    • Center for the Study of Plasma Microturbulence
    • Center for Gyrokinetic Simulation of Energetic Particle Turbulence and Transport (GSEP)
    • Prototype FSP – Simulation of Waves in MHD (SWIM)
    • Prototype FSP – Center for Plasma and Edge Studies (CPES)
  – Collaborations with ITPA and BPO.

• Theory and simulation are not only used on C-Mod for interpretation but also for guidance and program / experimental planning.
Research Goals for Understanding Core Transport Physics on C-Mod

• Determine role of ITG, TEM and ETG on turbulent transport in L and H mode plasmas with equilibrated $T_i$, $T_e$:
  – Use GS2, GYRO, including comparisons with synthetic diagnostics.

• Understand ITB formation and control:
  – Use GYRO and GS2 simulations to distinguish ITG vs. TEM turbulent roles.

• Finish modifications to GYRO and GS2 to simulate momentum fluxes and compare with new profile measurements.

• Assess role of magnetic shear modification due to LHCD in ITB formation using GS2

• Study particle and impurity transport
  – Relation to drift wave turbulence (ITG, TEM)
Core Transport Physics Program on C-Mod Benefits from Gyrokinetic Simulation Program

• **Basic Theory:**
  – New nonlinear upshift of TEM critical density gradient, relevant to C-Mod ITB, increases with collisionality (Ernst, IAEA '06)

• **Developed interface and analysis software to enable simulations of experiments**
  – GS2_PREP – (Ernst, PoP, 2000)
  – fiTS – (Ernst and Zhurovich)

• **Thesis research involving turbulence simulation:**
  – Nonlinear GS2 simulations of ITB onset (Zhurovich, Ernst, Fiore)
  – PCI fluctuations and GS2 linear code studies (Lin, Porkolab, Ernst)
  – PCI fluctuations and comparison with GYRO linear and nonlinear simulations (Lin, Porkolab, Rost, Candy (GA), Mikkelson (PPPL))
  – GYRO simulations of lithium pellet striations (Bose, Ernst)

• **Gyrokinetic simulations of C-Mod H-mode plasmas**
  – GS2 (Mikkelson – PPPL and Dorland – U. Md.)
    • Studied collisionality dependence of Dimits shift in C-Mod
Spectrum of Density Fluctuations due to TEM Turbulence Reproduced by Gyrokinetic Simulation and Correlated to ITB Control by ICRH

- Synthetic PCI diagnostic in nonlinear GS2 enables first of kind comparison of wavelength spectra.

- TEM turbulence observed to increase in simulation with on-axis ICRH (1.22 sec) relative to off-axis ICRH only (1.05 sec).

- New PSFC cluster will allow these nonlinear studies to continue “in-house”

D. Ernst, PoP, 2004
Macroscopic MHD Research on C-Mod has Strong Interaction Between Theory, Simulation, and Measurements

• Studies of Alfven cascades and TAE modes in Alcator C-Mod:
  – NOVA simulations of frequency spectra of Alfven cascades under reverse shear conditions:
    • Edlund, Porkolab (MIT), Breizman (UT), Gorelenkov, Kramer (PPPL) – IAEA (2006)
  – Synthetic PCI diagnostic code to interpret mode structure of Alfven cascades:
    • Edlund, Porkolab, IAEA (2006)
  – Effect of fast ion $\beta$ on TAE mode frequency
    • Snipes, Jaeger, APS (2006)

• Simulations of gas-jet mitigation experiments on C-Mod:
  – Simulations with NIMROD and KPRAD
    • (Izzo 2004, Granetz, 2006)
Importance of Pressure (and Gradient) Gradient Terms on TAE Mode Frequency has Recently Been Elucidated on C-Mod

- Minimum frequency measurements of RSAEs from PCI data shows a strong correlation between $f_{\text{min}}^2$ and $T_e$.
  - Edlund, Porkolab (2008)

- Comparison of NOVA data and a theoretical form (Breizman et al, Physics of Plasmas 2005, Gorolenkov 2006) also show generally good agreement when realistic temperature gradients are included.
• 2/1 mode appears first and stochastic fields form at the edge, eventually destroying all field lines outside q=1

• 1/1 mode levels core temperature by swapping cold island with hot magnetic axis
Future Plans for Macroscopic MHD

• Understand the role of realistic ICRF-generated fast ion distributions in excitation of unstable AE and Alfven Cascades:
  – Better implementation of fast ion distributions from AORSA-CQL3D and TORIC-CQL3D in NOVA-K:
    • Compare these synthetic NOVA-K predictions for mode stability with data.
  – Use SparSpec code to interpret magnetic data on C-Mod to determine toroidal mode number spectrum of TAE’s

• Continue gas-jet simulations with NIMROD+KPRAD
**Plans for Pedestal and Boundary Physics Studies will Emphasize Theory and Advanced Simulation**

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<td>M. Umansky, X.Q. Xu, R. Cohen, D. Ryutov (LLNL)</td>
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<td>P. Catto (MIT), A. Simakov (LANL)</td>
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<td>A. Pigarov, S. Krashininnikov (UCSD)</td>
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EM turbulence may be a unifying theme for near SOL and pedestal transport physics

- **L-mode and H-mode near SOL** both have:
  - pedestals
  - gradients which appear controlled by EM instabilities
  $\Rightarrow$ ‘critical $\alpha_{\text{MHD}}$’ with $\nu^*$ dependence

- **Theory suggests other controlling parameters other than $\nu^*$.**
  - Magnetic shear
  - Flow shear

- **Plans**
  - Use Ohmic L-H transition to compare to Guzdar and other models (Rogers, and Drake)
Plan to Test Theoretical and Simulation Predictions for L-H Transition

- **Theoretical predictions** (Guzdar) are midway between measurements with gradB drift in favorable and unfavorable directions.
  - Theory doesn't include the equilibrium flow effects that we think are important to explain the topology dependence.
- **Plan to also compare with simulations using**
  - GEM code (Scott) that do not see an L-H bifurcation.
Long Terms Plans for Pedestal and Edge
Emphasize Theory and Simulation

• Test predictions of $E_r$ for pedestal by comparing with recent C-Mod data:
  – $E_r$ from density, temperature, flow measurements of Boron impurities:
    • Compare Pfirsh-Schlüter prediction for the shape of $E_r$
    • Compare neoclassical flow predictions with measurements.
    • Examine effects of magnetic topology on flow inside the separatrix
    • Examine role of $E \times B$ shear reduction in L-H transition.

• Application of advanced simulation codes to C-Mod edge:
  – Use ELITE and M3D to study edge stability.
  – Validate 5D neoclassical edge transport codes (XGC0, XGC1 -CPES) and TEMPEST code (LLNL) against pedestal structure and scalings from C-Mod data.
  – Simulate L-H transitions and complete ELM cycle using integrated codes developed through on-going CPES Fusion Simulation Project, as they become available.
Accurate Computation of ICRF-Generated Energetic Ion Will be a High Priority in 2008-2013

• Accurate calculation of 3D ion tail distributions is important for several key physics areas on C-Mod:
  – MHD studies of Alfvén cascades.
  – Sawtooth modification experiments using ICRF.
  – Transport analysis of standard and improved confinement (ITB) regimes.
  – Analysis of ICRF heated plasmas with significant toroidal rotation.

• Continue CNPA synthetic diagnostic analysis with:
  – Combined CQL3D and AORS/TORIC:
    • Analyze where FLR approximation breaks down.
  – Combined ORBIT RF with AORS/TORIC:
    • Assess importance of finite ion drift orbit effects.
  – Research activities to be carried out through RF SciDAC Center
Progress has been made in Developing a Predictive Capability for Nonthermal Ion Tail Evolution

AORSA/CQL3D Simulation – $10^3$ processor hours

Using a Maxwellian fit to the CNPA data gives $T_{ion} \sim 70$ keV.

E. F. Jaeger, R. Harvey, L. Berry, ORNL

3D \( (r, V_{\perp}, V//) \) distribution function from CQL3D – AORSA reproduces CNPA measurements using a synthetic code diagnostic

Synthetic diagnostic code developed through a close collaboration between theory and experiment (V. Tang and R. Harvey)

ICRF Current and Pressure Profile Control

Emphasis will be to apply simulation capability to mode conversion current drive (MCCD) and flow drive applications.

• **Mode Conversion Current Drive:**
  – Compute MCCD using TORIC and AORSA fields in CQL3D with appropriate quasilinear diffusion coefficient:
    • Requires correct theoretical formulation.

• **Identify scenarios in C-Mod that maximize ion damping of mode converted ICRF wave (IBW or ICW):**
  – Compute associated flow drive.
ICRF Current and Pressure Profile Control

Emphasis in 2008-2010 will be to improve simulation capability already developed for ICRF mode conversion

- Improve synthetic PCI diagnostic code calculations:
  - Resolve scale differences between predicted and measured signals:
  - Construct and compare PCI signals from AORSA and TORIC fields.
Ability to predict 3-D($p_\perp$, $p_\parallel$, $r$) electron distribution function and LH current using CQL3D-GENRAY has been tested on C-Mod.

- Self-consistent nonthermal $f_e$ is used in synthetic diagnostics for hard X-ray and EC emission.
- HXR Spectra from synthetic code agree with measured profiles in magnitude (no renormalization!) – but are narrower.

- Predicted off-axis LH current density reproduces “shoulder” in MSE measurements.

Ko, Schmidt
Bonoli, Harvey, Parker, Scott, Wright
Combined LH Full-wave – Fokker Planck Simulation is major goal for 2008-2010

- Full-wave effects such as focusing and diffraction are being investigated as possible reason for discrepancy in hard x-ray predictions.

- Full-wave LH simulations performed on the Loki cluster at MIT (30 hours @ 256 processors).

- Electron and ion plasma response in TORIC can now be evaluated using the nonthermal $f_e$ from CQL3D (E. Valeo, C.K. Phillips, J. Wright).

- Final step is to reconstruct $D_{QL}$ from TORIC and pass it to CQL3D.

- This work is part of the 2008 DoE JOULE Theory Milestone
Linear ICRF Antenna Coupling will be achieved through TOPICA – TORIC Code Integration

- **TOPICA**: (Torino)
  - Fully 3D solid antenna structure model (including FS, box,…)
  - Code runs on Marshall cluster (parallel version can model the ITER ICRF antenna).

- **TORIC**: (MIT)
  - Toroidal full-wave solver provides the plasma response through an admittance matrix that includes effects due to curvature of the antenna and poloidal mode coupling.
  - This activity is a main thrust of the RF SciDAC Project.
Nonlinear ICRF Antenna Sheath Studies

- Implement a metal wall (or general sheath) boundary condition (BC) in TORIC that accounts for misalignment between metal wall and B.
  - Compute the **linear ICRF** fields from TOPICA-TORIC.
  - Evaluate the metal wall (sheath) BC for TORIC using the linear fields.
  - Re-compute the TORIC fields with the new metal wall BC.
  - Repeat process above to convergence.
  - Get sheath dissipation from converged fields.
- Investigate sheath dissipation for minority heating schemes in C-Mod:
  - Strong single pass damping – D (H)
  - Weak single pass damping – D (³He)
- Time domain simulations using 3D EM field solver – VORPAL
  - Fully implicit time domain dielectric response module has been implemented for electrons and ions.
  - Use PIC-treatment for ion response (fully nonlinear).
  - Done in collaboration with RF SciDAC Center
Time Dependent Integrated Scenario Modeling of C-Mod Plasmas began in 2003-2008 using TSC

- Simulations presently use TSC – LSC:
  - TSC performs discharge evolution using 1.5D transport equations, free boundary MHD solver, and LSC code for the LHCD.
  - Model profiles for ICRF heating.
  - Tang-Coppi micro-instability based $\chi_e$

- TSC – LSC Simulation with H-mode Plasmas Can Produce High $f_{NI}$ and Drive $q(0) > 1$ (C. Kessel, PPPL):

![Graph showing ICRF and LH on effects on current and q-profiles.](image-url)
Goal in 2008-2013 will be to Increase the Realism of Time Dependent Integrated Scenario Modeling

- Active efforts through ITPA-SSO, RF SciDAC Project, and SWIM/FACETS FSP Projects to improve the ICRH, LHCD, and transport models used in time dependent TSC simulations:
  - Incorporate 3D Fokker Planck simulations for LHCD from CQL3D-GENRAY:
  - Include self-consistent ICRF tail formation from AORSA/TORIC – CQL3D:
  - Include predictive transport capability through TGLF:
  - **Partial solution is to perform combined simulations with TRANSP and TSC:**
    - TRANSP computes LHCD using LSC, ICRH using TORIC, and transport using GLF23.
    - Plasma is evolved using these source terms in TSC.
- **Need to develop kinetic closure relations for coupling RF and MHD codes** (J. Ramos, CSWIM Project)
  - Application to NTM stabilization via ECCD and LHCD.
  - Application to sawtooth stabilization via energetic particles (ICRF).
  - Spatial regions exist near rational flux surfaces within which RF, the kinetic evolution of the velocity distribution, and extended MHD phenomena are all tightly coupled.
Ultimate solution will be to employ parallel frameworks being developed under existing Fusion Simulation Projects

“Integrated Plasma Simulator -IPS” developed through SWIM Project.

D. B. Batchelor
New PSFC Parallel Computing Cluster - Loki

- 256 Opteron processors in 64 nodes.
- Infinipath and Gigabit network connectivity.
- Can be upgraded to 512 cores with quad core processors.

• Nonlinear GK simulations can be done in-house.

• Full-wave LH field simulations can be done in 4.6 hours (required six days on old Marshall cluster).

T. Baker, D. Ernst, J. Wright
Summary

• Alcator C-Mod benefits from advances in theory and simulations and promotes advances in the areas of:
  – Transport
    • Gyrokinetic studies of ITB formation and control
    • Synthetic PCI diagnostic for TEM turbulence
  – Wave – particle interactions in the ICRF and LHRF regimes
    • Predictive LHCD capability using CQL3D
    • Synthetic diagnostic codes for hard x-ray emission, CNPA, and nonthermal ECE
    • Predictive capability for minority heating and quasilinear tail formation.
    • Full-wave LHRF studies using TORIC LH
    • 3D ICRF antenna modeling using TOPICA (Torino)
  – Understanding TAE mode and Alfvén cascade observations in C-Mod using NOVA-K
  – Integrated scenario development using TSC & TRANSP
  – Disruption mitigation using NIMROD, KPRAD
  – Pedestal and edge modeling with ELITE, BOUT, ESEL, GEM
  – Graduate student training a key part of the program
Summary

• During the next five years we plan to continue to develop a predictive capability in these areas by:
  – Taking advantage of theoretical advances.
  – Employing advanced simulation codes and integrated models when available.
• Targeting key problem areas:
  – Radial electric field in the edge
  – ICRF – antenna edge interactions
  – Full-wave effects in LH wave propagation
  – Simulation of the ELM cycle.
  – Prediction of pedestal characteristics
  – Transport of energetic particles due to Alfven wave activity