Outline

• Review highlights in theory and simulation support for Alcator C-Mod in the following areas:
  – Core transport physics.
  – MHD phenomena – runaway electron confinement and energetic particles.
  – Pedestal and Plasma boundary.
  – Wave – plasma interactions.
  – Integrated scenario modeling.

• Progress and challenges in each area will be discussed, as well as future plans, especially as they impact the C-Mod program.
Collaborations

• Theory and simulation research consists of active collaborations through:
  – ITPA and BPO (ITER and Burning Plasma Organizations).
  – PPPL, UT, IPP (Asdex-Upgrade),
  – Individual initiatives between C-Mod personnel and theorists within MIT (PSFC Theory Group) and outside MIT.
  – SciDAC Centers:
    • Center for Simulation of Wave-Plasma Interactions - (CSWPI)
    • Center for Extended MHD Modeling - (CEMM)
    • Center for the Study of Plasma Microturbulence - (CSPM)
    • Center for Gyrokinetic Simulation of Energetic Particle Turbulence and Transport - (GSEP)
    • Center for Simulation of Energetic Particle Physics – (CSEP)
    • Prototype FSP – Simulation of Waves in MHD (SWIM)
    • Prototype FSP – Center for Plasma and Edge Studies (CPES)
  – Anticipate significant collaboration with the upcoming Fusion Simulation Project (FSP).

• Theory and simulation research on C-Mod provides support for interpretation and guidance of experiment as well as for program / experimental planning.
Establishment of a Turbulence Simulation User Group at the PSFC has Facilitated Collaboration Among C-Mod Personnel and Theorists

- Jointly organized by A. White, D. Ernst, and M. Greenwald:
  - Group meets once a week for 1-2 hours.
  - Active role by graduate students.
  - Involves remote participation by outside collaborators.
  - Topics covered include theory and simulation.
  - Some recent talk titles at the user group meeting have been:
    - “Profile fitting and profile analysis”
    - “Validation”
    - “Critical Gradient – Theory for ITG”
    - “TGLF at C-Mod and inboard/outboard edge turbulence”
    - “Integrated Plasma Simulator”
    - “RF Modules in TRANSP”
Recent progress in turbulent transport studies features close coupling between experiment, measurements, and gyrokinetic (GK) simulations

• Studies to elucidate the role of electron transport in low density Alcator regime [Porkolab, Dorris – (also see talk by Greenwald)].

• Experiments carried out to understand role of TEM in control of ITB’s in C-Mod and study role of collisionality and $T_e / T_i$ in neo-Alcator regime [D. Ernst].

• New CECE diagnostic designed using nonlinear / linear GYRO simulations [A. White, N. Howard, J. Candy, R. Waltz – also see talk by Greenwald)].

• Major upgrade to fitting tools for TRANSP & GK code data preparation [D. Ernst].
Using modulated on-axis ICRH to control fluctuations in an Internal Transport Barrier

- Experiment motivated by 2006 comparison of GS2 TEM fluctuation spectra with PCI using synthetic diagnostic [Ernst et al., IAEA (2006) TH/4-1].
- ICRF power modulation used to rule out edge fluctuations in the line-integrated PCI signal.
- The bursts on PCI are in phase with Te0 on-axis, while edge fluctuations diminish during the bursts.
- Central densities > 6e20 m\(^{-3}\) attained with neon puffing.
- Greatly improved profile and fluctuation measurements (full suite).
- On-axis heating drives strong density fluctuations and particle and thermal transport in ITB.

D. R. Ernst, APS (2010).
Major upgrades have been made to transport analysis preparation tools

- **FiTS is the main tool used to prepare profile data for TRANSP**
  - FiTS creates B-spline + edge tanh fit using available $T_e$ & $n_e$ data.
  - Added Monte Carlo error analysis of density profile fits (trials can be saved),
  - Error estimate for gradient (important for gyrokinetic simulations).
  - Improved automated fit quality.
  - Both graphical and command-line fits now callable from IDL.

- **Database driven web interface connecting gyrokinetic simulations with experimental data is also nearing release:**
  - Reads TRANSP data from MDSPLUS servers for most experiments (C-Mod, DIII-D, NSTX, TFTR, JET, MAST, etc.) and prepares input data for validation.
  - Supports GS2 and GYRO (will be extensible).
Future plans call for GK model validation and using simulation capability to understand core transport physics

- **Application of TGLF to C-Mod discharges and comparison with nonlinear stability analyses from GYRO and TGYRO** [G. Staebler (GA), Y. Ma, N. Howard, and A. White].

- **Continue investigations of ITG, TEM and ETG roles in turbulent transport in C-Mod plasmas with equilibrated $T_i$, $T_e$:** [Ernst, Porkolab, Dorris, Ennever]
  - Use GS2, GYRO, including comparisons with synthetic diagnostics for PCI.
  - Study role of collisionality and $T_e / T_i$ in neo-Alcator regime.

- **Continue studies of ITB formation and control** [Ernst, Fiore]:
  - Use TRANSP, GYRO and GS2 simulations to distinguish ITG vs. TEM turbulent roles.

- **Assess role of LHCD:** [Ernst, Fiore, Hubbard, Parker, Porkolab, Rice, Shiraiwa, Wilson]
  - ITB formation via magnetic shear modification.
  - Modification of core plasma rotation.
  - Modification of pedestal density and temperature.

- **Study particle and impurity transport:** [Ernst, Greenwald, Howard]
  - Determine relationship to drift wave turbulence (ITG, TEM).
  - GK simulations of impurity transport compared to laser blow-off experiments.
Plans For Future Transport Experiments and Turbulence Characterization with PCI

- By introducing a second impurity species with a $Z_i$ of 8, as the $Z_{\text{eff}}$ is increased and density lowered in accordance with ohmic plasmas, $\chi_i$ is reduced to, and $\chi_e$ remains at experimentally relevant values.
- Not collisional effect ($Z_i=42$ will not work).
- Will carry out controlled seeding experiments (Ne, N) to test the theoretical predictions.
- Will compare PCI synthetic diagnostic predictions to experimental observations of turbulence spectrum with $E_r$ Doppler shift to separate spectrum from edge turbulence.
- Will expand results with auxiliary heating (ICRH MC, ICRH, LH-HTG) to study impact of $T_e/T_i$ and relate to turbulence spectrum.
- Expand results to higher densities where $Z_{\text{eff}} = 1.2$ or less (H-mode, I-mode).
- Need to study core transport ($r/a < 0.5$) where electron drift waves ($U/c_s \leq 6$) may dominate $→$ not in GYRO:
  - Role of sawteeth and heat pinch must be assessed.
  - Need theory.

\[\chi_e\] and [\chi_i] from TGLF Simulations

Dorris and Porkolab, TTF and EPS 2011
Future plans call for investigating hidden variables in Neo-Alcator Scaling

- Experimental proposal motivated by theory.
- Density does not enter delta-f gyrokinetic-Maxwell equations, except through collisionality.
- Observed neo-Alcator scaling of confinement time with density may be a result of strong variations in $T_e/T_i$ and collisionality.
- Both variations qualitatively consistent with observed scaling, if ITG/TEM turbulence dominates.
- Use mode conversion electron heating to
  - Scan density at constant $T_e/T_i$
  - Scan $T_e/T_i$ at constant density

Electron thermal transport is a focus of the SciDAC Center for Study of Plasma Microturbulence [D. Ernst is MIT PI]
MHD: Disruption runaway electron (RE) studies

- **Initial experiments** on LH-generated runaway electrons (RE’s) in normal C-Mod equilibria found a lack of RE’s in the disruption current quench.
- A survey of RE observations from a number of tokamaks led to the hypothesis that disruption RE’s are much more prevalent in low-elongation limiter devices compared to elongated diverted ones.
- An experiment to explicitly test this hypothesis was performed in C-Mod and simulations of these experiments have been highly successful and informative [V. Izzo, IAEA, FEC 2010]:
  - Model:
    - NIMROD for extended MHD.
    - KPRAD for impurity seeding (“Ar pellet-model” for core and edge peaked “Ar gas-jet model”).
    - Guiding-center drift motion of test (trace) population of REs is calculated as MHD fields evolve
    - Studied sequence of events, effects of plasma shape, fueling profile, and machine size.
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  – Studied sequence of events, effects of plasma shape, fueling profile, and machine size.
NIMROD modeling shows differences between high and low $\kappa$

At low $\kappa$, $n = 1$ is not as dominant, and destruction of flux surfaces is not as extensive.

Diverted plasma: REs lost due to transport on stochastic fields.

Limited plasma: REs lost due to $n=1$ shift of equilibrium into center column.

Core-peaked Ar case has immediate 1/1 mode onset, loss of nearly all REs in one event.

Edge-peaked Ar case has delayed 1/1 mode onset, delayed loss of core REs.

*V. Izzo*
Total RE loss fraction simulated by NIMROD decreases as machine size (R) increases [from Rechester – Rosenbluth $\tau_{\text{RunElec}} \sim R^2/D \sim R^3$]

V. Izzo
Plans for Macroscopic MHD

• **Continue analysis of experiments with LH seeded runaway electrons:**
  – Further experimental & modeling scoping should continue to test the predictive capability for runaway electron confinement in ITER.

• **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: (CSEP& RF SciDAC Centers)
    • Compare these synthetic NOVA-K predictions for mode stability with data.

• **Assess viability of ICRF for sawtooth modification via:**
  – ICRF-generated minority tail (energetic particle stabilization).
  – Local shear modification via mode conversion current drive (MCCD).
  – Work with J. Ramos and SWIM FSP Project.
Theoretical studies of flows in the pedestal (banana regime) demonstrate the radial electric field ($E_r$) modifies ion orbits.

**C-Mod:** Marr, Lipschultz, McDermott (plateau shaded)

Theory without $E_r$: standard banana

Theory with finite $E_r$: Kagan, Landreman, Catto

Bootstrap current also altered!

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**Diagram:**

- **C-Mod**
- **Without $E_r$**
- **With $E_r$**

**Axes:**
- **Poloidal flow (km/s)**
- **Major radius [m]**
- **Predicted peak heights (km/s)**
- **Measured peak heights (km/s)**

**Labels:**
- **P. Catto, Landreman, Kagan, Lipschultz**
Future Plans: Use C-Mod data to test pedestal models and for edge code validation

- Much of this work is ongoing through the 2011 FES Joint Research Target (along with DIII-D, NSTX).
- Use measurements to test theoretical predictions of edge $E_r$, flows, pedestal impurity asymmetries:
  - Use divergent-free form of impurity flux to more carefully measure impurity density in-out asymmetry (Churchill, Lipschultz, Catto).
  - Improve finite $E_r$ model by adding ellipticity and, if possible, up-down asymmetry (LSN vs USN) (Catto, Lipschultz, Churchill + visitor).
- Analyze roles of pedestal/SOL flows, neutral particles, and the quasi-coherent mode on pedestal structure using fluid transport and turbulence codes UEDGE and BOUT (LLNL)
- Evaluate neoclassical transport from NEO and XGC0 (GA, CPES).
- Ongoing comparisons to the EPED model for pedestal structure (GA).

Collaborators are an essential resource in this effort!
Future Plans: Use C-Mod data to test pedestal models and for edge code validation

• **Continue ELM stability studies** *(GA, LLNL, MIT, CPES)*:
  – Characterization of peeling-balloonning mode stability boundary with ELITE, BOUT++, using variation in edge current/pressure gradient
  – What is the impact of varying model for pedestal bootstrap current?
  – Evaluate effects of extended and two-fluid MHD terms with M3D code
  – Quantitatively assess impact of dissipation, rotation, and diamagnetic stabilization

• **Explore use of GYRO, TGLF in pedestal region** *(GA, LLNL)*:
  – Linear growth rates for ETG, TEM, KBM
  – Assess feasibility of nonlinear gyrokinetic simulations and comparison to turbulence measurements

• **Validation of full-f guiding center simulation with EM turbulence**: XGC1 *(CPES).*

*Collaborators are an essential resource in this effort!*
Boundary: ACRONYM is a synthetic diagnostic for an accelerator-based PFC diagnostic on Alcator C-Mod

- ACRONYM* is a Monte Carlo particle transport-in-matter simulation capable of modelling and detecting deuteron-induced nuclear reactions to enable analysis of plasma facing component (PFC) surface conditions.
- ACRONYM features:
  - Simulates passage of particles through matter with the Geant4 toolkit.
  - Realistic C-Mod geometry and magnetic fields
  - RFQ accelerator 0.9 MeV deuteron beam
  - Full models of neutron and gamma detectors
  - Deuteron-induced nuclear reactions for PFC surface analysis
  - Parallel architecture (Open MPI) for scalable processing

* Alcator C-Mod RFQ Official Neutron Yield Model

An incident deuteron beam (yellow) reacts with boron film on C-Mod’s outer divertor tiles (red) to produce gamma rays (green)

An incident gamma ray (green) induces scintillation light (magenta) that is absorbed (orange) by an avalanche photodiode (red)

Z. Hartwig
Future Plans – Boundary Physics

- Use SOLT code to model well-diagnosed L-Mode discharges in C-Mod (collaboration with Lodestar).
- Model edge turbulence in same L-Mode discharges using BOUT (collaboration with LLNL).
- Massively parallel implementation of ACRONYM synthetic diagnostic (Z. Hartwig).
  - ACRONYM will be a critical tool to interpret experimental data once the RFQ diagnostic is installed.
  - ACRONYM will enable the optimization of boron layer thickness measurements (detector placement, detector design, required measurement times, etc)
ICRF Minority Heating Studies: Progress and Plans

• Accurate calculation of 3D ion tail distributions is important for several key physics areas on C-Mod:
  – MHD studies of Alfvén cascades (Edlund, Porkolab et al, POP, 2009) and sawtooth modification experiments (Wukitch et al, PoP, 2009) using ICRF.
  – Transport analysis of standard and improved confinement (ITB) regimes and analysis of ICRF heated plasmas with significant toroidal rotation.

• Progress made in validating predictive capability for non-thermal ion tail production: [Bader, Pace, Harvey, Jaeger, Bonoli]
  – Data from CNPA diagnostic has been compared with synthetic diagnostic signal based on non-thermal ion tail from combined CQL3D and AORSA.
  – Results thus far properly simulate energy dependence of CNPA spectra but point to possible importance of radial losses.

• Future work:
  – Combine Monte Carlo codes sMC or ORBIT RF with AORSA/TORIC to include finite orbit width effects: [Choi, Green]
  – Simulate time dependence of minority tail formation and compare with modulation experiment: [Bader]
CNPA diagnostic data on C-Mod is being used to test simulation capability for minority ICRF heating

- Fast ion tail was computed by iterating the steady state solution from the Fokker-Planck code CQL3D with the full-wave solver AORSA-2D.
- Simulations show good agreement at $R = 76$ cm.
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- Fast ion tail was computed by iterating the steady state solution from the Fokker-Planck code CQL3D with the full-wave solver AORSA-2D.
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- Fast ion tail was computed by iterating the steady state solution from the Fokker-Planck code CQL3D with the full-wave solver AORSA-2D.
- Simulations show good agreement at $R = 76$ cm, reasonable agreement at $R = 69$ cm, and poor agreement at $R = 66$ cm.
- The synthetic diagnostic tends to have the largest discrepancy at or near the ICRF resonance.
- Quasi-linear theory may not apply ($\Delta E_f \approx E_f$) or finite ion orbit width effects may be important.
ICRF Current and Pressure Profile Control: Progress and Plans

- Emphasis is to apply simulation capability to mode conversion current drive (MCCD) and flow drive applications.
- Progress in verification of mode converted ICRF wave fields [Tsujii, Porkolab, Jaeger, Wright]:
  - Simulated PCI signals from AORSA wave fields agree well with measured signals in strong damping regimes \([n_H / n_e < 10\% \text{ and } n_{\text{He-3}} / n_e > 10-12\%]\), but disagree in weak damping cases.
  - Calculation relies on proper 3-D electric field reconstruction.
- Plans:
  - Investigate possible missing physics in full-wave codes (parasitic losses, nonlinear effects, etc) and study sensitivity of simulated PCI signal to plasma conditions and geometry.
  - Compute MCCD using TORIC and AORSA fields and apply to sawtooth modification experiments.
  - Understand discrepancy between measured and predicted flow drive (Y. Lin, E. F. Jaeger, M. Myra).
  - Understand the cause of the discrepancy (if it exists in C-Mod) between TS and ECE measurements of \(T_e\) that have been observed to disagree in cases when \(T_e(0) > 7\) keV: [A. White, Hubbard, Hughes, and Ma]:
    - CQL3D (modeling of distribution function), Genray (simulated EC emission), and ECESIM (simulated ECE spectra).
Fluctuation measurement with PCI consistent with 3-D ICRF full-wave simulations in strong damping regime

D(H) plasma, n_H/n_e = 0.08
Simulation: AORSA+CQL3D

Simulated and Measured PCI signals

N. Tsujii, M. Porkolab
Lower Hybrid Simulation Capability is being validated and used to understand core and coupling physics

- **Combined Full-wave spectral solver** and electron Fokker Planck code is now being validated against HXR data on C-Mod – TORIC LH & CQL3D: [Lee, Wright]
  - Self-consistent nonthermal electron distributions computed in weak and strong single pass damping regimes.
  - Wave momentum source due to LH waves has been computed.
  - First 3-D field reconstructions performed for an Alcator C-Mod size plasma that reproduce resonance cone behavior of LH wave.

- **Combined full-wave FEM solver and electron Fokker Planck code (LHEAF)** was developed and verified: [Meneghini, Shiraiwa, Parker]
  - FEM method allows straightforward inclusion of LH launcher, plasma edge, and vessel geometry.
  - Model is being validated against HXR and MSE data.
  - Model being used to study LH coupling at high density.

- **Combined ray tracing and electron Fokker Planck model (GENRAY-CQL3D)** has been used extensively to understand the LH density limit observed in C-Mod: [Wallace, R. Harvey, A. Smirnov, Shiraiwa]
  - Possible understanding of density limit in terms of collisional or parasitic edge losses as density is raised.
LHRF fields from TORLH-CQL3D have been used to compute the toroidal angular momentum source from LH waves → LH wave induces an ion counter-current toroidal rotation (Non-thermal electrons push ions)

- 3-D LH wave fields from coupled TORLH-CQL3D simulation were used to evaluate $D_{QL}$ in the wave momentum source:

$$\left\langle \int d^3 v (m_e R^2 \cdot \overline{D_{ql}} \cdot \nabla_e f_e) \right\rangle \psi$$

J. P. Lee, J. Wright, D. Ernst, P. Catto, R. Parker, Y. Podpaly, J. Rice

Future work:
- Repeat wave-momentum analysis on more C-Mod discharges.
- Include transport effects on rotation from gyrokinetics in ion stress tensor
- Collaboration with F. I. Parra and M. Barnes
Good agreement is obtained for measured and simulated current density profiles with LHCD in an MHD stable discharge. Predicted $I_{\text{plasma}}$ is 750 kA, while experimental is 800 kA.

Ray-tracing shows good agreement in terms of $I_{\text{plasma}}$, but computed LHCD profile shows local peak around $r/a \sim 0.5$, which is not shown in experiment.
Ray Tracing/Fokker-Planck Simulations Used to Understand LHCD Physics at High Density in C-Mod

- Ray tracing simulations without SOL predict $1/ne$ trend in hard x-ray (HXR) emission...
- But diverted discharges show steep drop in HXR emission above $10^{20}$ m$^{-3}$
- Magnitude of HXR emission correctly predicted when SOL absorption is included in the ray tracing model
- Proper treatment of parasitic edge losses is key to understanding loss of current drive at high $n_e$

**G. Wallace, R. Harvey, A. Smirnov**

### Table

<table>
<thead>
<tr>
<th>Line Averaged $n_e$ [m$^{-3}$]</th>
<th>Count Rate (Ch 9-24, 40-200 keV) [s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/ne</td>
<td>Line Integrated HXR Count Rate</td>
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<tr>
<td>USN, Gap &gt; 1 cm</td>
<td>Exp. Data</td>
</tr>
<tr>
<td>LSN, Gap &gt; 1 cm</td>
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</tr>
<tr>
<td>USN, Gap = 0.4 cm</td>
<td></td>
</tr>
<tr>
<td>Limited</td>
<td></td>
</tr>
</tbody>
</table>

### Diagram

- Modeling tools are now being used to test means of mitigating LHCD density limit on C-Mod.
LH coupling measurements agree with linear coupling theory, provided density profile has a millimetric vacuum layer, but does this vacuum gap really exist?

Density profile measurements from SOL reflectometer support vacuum layer theory.

Use nonlinear $\delta n$ due to ponderomotive force of LH wave in finite element full-wave code (LHEAF) to self-consistently compute coupled fields.

LH power required to achieve experimentally observed density profile is $\sim 4 \times$ experimental power, but results are preliminary.
Research efforts focused on understanding interactions of LHRF and ICRF waves with the SOL

• **Edge density fluctuations in the form of blobs can modify propagation properties of RF waves through refraction and diffraction:** [K. Hizanidis, A. K. Ram, Y. Kominis]
  – Developed a Fokker-Planck model for the scattering of RF waves by a random distribution of blobs.
  – The scattering can have two diffusive effects – one in real space and the other in wave vector space.
  – For electron cyclotron waves real space diffusion is important:
    • In ITER this could lead to EC waves missing the NTM island.
  – For lower hybrid waves wave vector space diffusion is important
    • Leads to a spreading of the parallel wave vectors and a reduction in the current drive efficiency.
  – **Future work - full wave theory to include diffractive effects.**

• **A nonlinear sheath boundary condition (BC) has been implemented in a new FEM solver (“rfSOL”) that accounts for misalignment between metal wall and B:** [H. Kohno with J. Myra, D. D’Ippolito, J. Č. Wright and J. Freidberg]
  – Wave equation solved only in region between LCFS and wall.
  – Plasma model includes both fast and slow waves.
  – Parallel code development completed.
  – **Discovery of the existence of a sheath plasma wave (SPW) in 2-D simulations.**
Time dependent integrated scenario simulations using TSC have been on-going

- **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 $\chi_e$
  - Collaboration with PPPL.
- **Currently, TSC – LSC is being used to simulate LH current profile control experiments in C-Mod (see below):** [C. Kessel]

![Graph showing sawtooth onset time](image)

- $P_{LH} = 0.5 \text{ MW}$
- $n_e = 4 \times 10^{19} \text{m}^{-3}$ (red)
- $n_e = 7 \times 10^{19} \text{m}^{-3}$ (green)
- $n_e = 9 \times 10^{19} \text{m}^{-3}$ (blue)

Ohmic Reference (black) - $9 \times 10^{19} \text{m}^{-3}$
Plan to perform time dependent simulations of LH current profile control in Alcator C-Mod using a parallel framework - the Integrated Plasma Simulator (IPS)

- TSC for time dependent transport.
- Replace LSC by GENRAY/CQL3D for LH current drive.
- Replace ICRH model sources by either coupled AORSA/CQL3D or TORIC/CQL3D calculations.
- Use Porcelli model for sawtooth prediction.

D. B. Batchelor (ORNL), P. Bonoli, R. Harvey (CompX), C. Kessel (PPPL), J. Wright and the SWIM Project
Loki Parallel Computing Cluster continues to be an essential resource for C-Mod

- Developed and maintained by PSFC Theory Group – platform is now 600 cores.
- Near-continuous availability with user-friendly web tools written in-house.
- Loki continues to be the sole parallel computational resource for most PSFC students:
  - 1.8 Million CPU hours used in past year in 22,000 jobs
  - 50 users (19 intensive users)
- TORIC, GS2, GYRO, TGLF, NIMROD, SCEPTIC3D, CQL3D, ELMFIRE, TOPICA.

Ernst, Wright, Baker, Bonoli
PSFC High Performance Cluster - Loki Plans for 2011

- Stable ongoing cluster operations.
- Finish important upgrades (Wright, Baker, Ernst):
  - Storage sub-system upgrade (2 \(\rightarrow\) 25 TB).
  - Operating system upgrade.
  - During 8 week upgrade process, we have kept Loki seamlessly available by transforming a compute node into a temporary head node [Ernst].
- Investigate adding partial (half-time) software support personnel:
  - Support activities have placed a heavy burden on theory group [Ernst, Wright].
- Begin future technology/system configuration research.
  - Addition of a GPGPU subsystem upgrade.
- PSFC/Theory and C-Mod will also be sharing the cost of a separate analysis and data server (48 core and 25 TB).
Summary

• Theory Group at the PSFC combined with external collaborations has continued to provide key theory and simulation support for the C-Mod Project leading to advances in the areas of:
  
  – **Transport**
    • Gyrokinetic studies of electron and ion transport and ITB formation and control.
  
  – **Wave – particle interactions in the ICRF and LHRF regimes**
    • Accurate wave fields and nonthermal particle distributions for synthetic diagnostic codes for Phase Contrast Imaging, hard X-ray emission and CNPA.
    • Predictive capability for minority heating and quasilinear tail formation.
    • Ray tracing and full-wave studies of the LH “density limit”.
    • Development of ICRF and LHRF coupling models.
  
  – **Pedestal physics**
    • Interpreting measurements of plasma flow and $E_t$ in the edge.
Summary

- Contributions of theory and simulation collaborations (continued):
  - Interpretation of LH seeded runaway electron (RE) experiments:
    - Role of plasma shape and device size in determining RE confinement.
  - Integrated scenario development using TSC-TRANSP and the IPS parallel computing framework:
    - Successful simulation of sawtooth delay and modification in C-Mod and understanding in terms of LH current profile control.
  - Development of widely used interfaces and tools for gyrokinetic analysis of C-Mod discharges.
  - Computing cluster support
    - Stable, state of the art high performance computing architecture.
Back Up Slides
Database Driven Web Interface Connecting Gyrokinetic Simulations with Experimental Data

• Nearing initial release.

• Reads TRANSP data from MDSPLUS servers for most experiments (C-Mod, DIII-D, NSTX, TFTR, JET, MAST, etc.) and prepares input data for validation.

• Supports GS2 and GYRO (will be extensible).

• Supports all TRANSP runs, with extensive smoothing options, species aggregation, choice of grid, etc.

• Back-end based on GS2_PREP, in continuous use by several researchers over past decade[D. R. Ernst, Phys. Plasmas (1998, 2004)].

• No software to install, eliminating duplication of effort and barriers to entry.

• In conjunction with this effort we are developing a comprehensive simulation metadata catalog - [collaboration with CSPM, SWIM, FSP and DIII-D].

• Webgraph: First publication quality java scientific plotter

• Written at MIT (2003-2006) by Geoffrey Catto, Bo Feng, Darin Ernst

A. Suarez and D. R. Ernst, APS (2005)
D. R. Ernst, A. Suarez, G. Catto, B. Feng, APS (2010)
Simulation will be important for interpreting proposed TS / ECE experiments on C-Mod

- In sufficiently dense, optically thick plasmas TS and ECE measurements are in very good agreement.

- However, in ICRH and NB heated discharges at JET and TFTR, TS and ECE measurements of Te have been observed to disagree in cases when Te(0) > 7 keV and the cause of disagreement is not known.

- Resolving the discrepancy between TS and ECE measurements is an ITPA Joint Experiment in 2010/2011, and requires tokamak plasmas that can be heated to Te(0) > 7 keV without creating nonthermal electrons (e.g. ICRH, Beams, Fast Wave)

- Alcator C-Mod and DII-D can contribute jointly to this effort, and PSFC can help to provide essential modeling support.

- Theory/modeling that will be needed to understand the cause of the discrepancy (if it exists):
  - CQL3D (modeling of distribution function)
  - Genray (simulated EC emission)
  - ECESIM (simulated ECE spectra)
Flow change is related to change in the bootstrap current

- Ion temperature gradient term in banana regime poloidal flow modified: \( u \approx (c / B_p) d\Phi / dr \)
  \[
  V_{i, pol}^{\text{pol}} \approx \frac{1.17 c}{eB} \frac{\partial T_i}{\partial r} A \left( \frac{u^2}{v_i^2} \right)
  \]

- Banana ions & Pfirsch-Schluter impurities:
  \[
  V_z^{\text{pol}} \approx \frac{c}{eB} \left( \frac{1}{n_i} \frac{\partial p_i}{\partial r} - \frac{1}{Z_i n_z} \frac{\partial p_z}{\partial r} \right)
  \]

- Bootstrap current (Z=1): No direct \( E_r \) effects on electrons, but know about \( E_r \) via friction between ion and electron flows
  \[
  J_{bs}^\parallel \approx -2.4 \frac{c \sqrt{\varepsilon}}{B_p} \left[ \frac{dp}{dr} - 0.74 n_e \frac{\partial T_e}{\partial r} - 1.17 A \left( \frac{u^2}{v_i^2} \right) n_e \frac{\partial T_i}{\partial r} \right]
  \]

- Increased bootstrap current in pedestal! 
  
  P. Catto
Alcator C-Mod deposits ~micron-thick boron layers onto its PFCs to achieve high-performance plasma discharges. Historically, we have been completely blind to the boron deposition efficiency, coverage of the first wall, and time evolution in response to plasma conditions.

ACRONYM is capable of modeling all steps in deuteron-induced nuclear reaction analysis to measure boron layer thickness over a large fraction of the first wall:
- Track the injected deuterons through the magnetic field
- Model deuteron-induced nuclear reactions in boron
- Track induced gammas through C-Mod geometry
- Model detection of gammas with scintillation detectors
- Output realistic detector pulse height spectra

ACRONYM is enabling the optimization of boron layer thickness measurements (detector placement, detector design, required measurement times, etc)

ACRONYM will be a critical tool to interpret experimental data once the diagnostic is installed.

Z. Hartwig
For 60 deg phasing case, discrepancies between simulated and measured current density profiles may be related to presence of MHD instabilities.

LHEAF prediction is hollower than the observation. In experiment, the q-profile is kept broader until $q_0 \rightarrow 2$ and the $n=1/m=2$ mode is destabilized.

(Would the current profile have evolved as LHEAF predicts without instabilities?)
Kinetic Theory for RF Wave-Particle Interactions

• Derived kinetic equation in collisionless plasmas
  • Long mean-free path formalism
• Different from the usual quasilinear theory
  • Diffusion tensor is time dependent

\[
\frac{\partial f(\overrightarrow{X}, t)}{\partial t} = \left( \frac{\partial}{\partial \overrightarrow{X}} \cdot \overrightarrow{D}(\overrightarrow{X}, t) \cdot \frac{\partial}{\partial \overrightarrow{X}} \right) f(\overrightarrow{X}, t)
\]

\[
\lim_{t \to \infty} \overrightarrow{D}(\overrightarrow{X}, t) \rightarrow \overrightarrow{D}_{QL}(\overrightarrow{X})
\]

\[
\lim_{t \to \infty} \frac{\partial}{\partial \overrightarrow{X}} \neq \lim_{t \to \infty} \frac{\partial}{\partial \overrightarrow{X}}
\]

• Future work - a numerical code which includes the collision operator is being developed.
Current Drive by Lower Hybrid Waves

Y. Kominis, A.K. Ram, K. Hizanidis
# Loki System Configuration

### 2010 vs 2011

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compute Nodes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processors (AMD)</td>
<td>Opteron 2352, 2378 2.10, 2.40 GHz</td>
<td>Opteron 2352, 2378 2.10, 2.40 GHz</td>
</tr>
<tr>
<td>Processor chips per node</td>
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<td>2</td>
</tr>
<tr>
<td>Cores per processor chip</td>
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<td>4</td>
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<tr>
<td>Data width</td>
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<td>64 bit</td>
</tr>
<tr>
<td>Memory</td>
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<td>16 GB DDR- 2 667</td>
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<tr>
<td>Disk space</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Network (s)</strong></td>
<td>1GB Ethernet 10 Gbs Infiniband 2.3</td>
<td>1GB Ethernet 10 Gbs Infiniband 2.3</td>
</tr>
<tr>
<td>Latency (microseconds)</td>
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<td>2.3</td>
</tr>
<tr>
<td><strong>Cluster totals (compute nodes)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total processor cores</td>
<td>600</td>
<td>600</td>
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<tr>
<td>Cluster memory</td>
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<td>940 GB</td>
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<tr>
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<td>18,750 GB</td>
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<tr>
<td><strong>Head Node</strong></td>
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<tr>
<td>Operating System</td>
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<td>Red Hat 5.5</td>
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<tr>
<td>Disk Subsystem</td>
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<td>~ 25 TB</td>
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