Agenda

Wednesday, January 24, 2006
13:00 Executive Session Rich Groebner
13:15 Welcome and Charge Miklos Porkolab
13:25 Comments from DoE Adam Rosenberg
13:30 Program Overview Earl Marmar
14:30 Lower Hybrid RF Ron Parker
15:00 Cryopump Brian LaBombard
15:20 Break
15:30 Plasma Boundary Bruce Lipschultz
16:00 Transport Martin Greenwald
16:30 Macro-stability Bob Granetz
17:00 Ion Cyclotron RF Steve Wukitch
17:30 Executive Session
19:30 Dinner (off-site)

Thursday, January 25
8:30 Facilities and Diagnostics Jim Irby
9:30 Theory and Modeling Paul Bonoli
10:15 Integrated Scenarios: H-Mode Baseline Steve Wolfe
10:45 Break
11:00 Integrated Scenarios: Advanced Scenarios Amanda Hubbard
11:30 Ideas Forum Jerry Hughes
11:45 Run Planning Steve Wolfe
12:00 Lunch (on-site)
13:00 Tour
14:00 Executive Session/Discussions with C-Mod team as desired

Friday, January 26
8:00 Executive Session - Draft response
11:00 Debriefing
12:00 Adjourn

Please turn off cell phone ringers during the sessions
Program Overview

Program Advisory Committee Meeting
January 24, 2007
presented by E. S. Marmar
on behalf of the C-Mod Group

*Equilibrated electrons-ions, no core momentum/particle sources, RF $I_p$ drive
Program Overview

- Research Highlights from FY06
- C-Mod Fusion Science and Technology Priorities
- ITPA Joint Experiments
- Contributions to Priority ITER R&D
- Comments on 2006 PAC Advice
- Priorities for Major Upgrades
- Budget
- Possible Themes for Next 5-Year Grant
C-Mod well positioned to help solve challenges for ITER

- Unique dimensional regimes
  - ITER B field, density, power density, plasma pressure
    - Disruption mitigation
    - Neutral opacity, Radiation Transport
  - High leverage database contributions
    - Dimensionally unique
    - Non-dimensional match to larger, lower field tokamaks
- ITER heating and current drive tools
  - Lower Hybrid Off-Axis CD
  - ICRF minority heating, MCCD
  - Torque and particle source free
    - Transport-driven rotation
- All-metal high-Z Plasma Facing Components
  - Molybdenum → Tungsten
    - Tritium retention, Impurity dynamics, Detachment
  - Wall conditioning; Low-Z wall coatings

\[
\begin{align*}
B_T &= 5.3 \, \text{T, } I_p = 1.6 \, \text{MA} \\
B &\leq 8.1 \, \text{T, } I \leq 2.0 \, \text{MA} \\
\beta_N &\leq 1.8, \ Z_{\text{eff}} \sim 1.5 \\
0.1 \times 10^{20} &< n_e < 10 \times 10^{20} \\
P_{||}(\text{SOL}) &\leq 0.5 \, \text{GW/m}^2
\end{align*}
\]

\[
\begin{align*}
B_T &= 5.3 \, \text{T, } I_p = 15 \, \text{MA} \\
\beta_N &= 1.75, \ Z_{\text{eff}} < 1.6 \\
n_e &= 1 \times 10^{20} \, \text{m}^{-3} \\
P_{||}(\text{SOL}) &\approx 1 \, \text{GW/m}^2
\end{align*}
\]
Research Highlights 2006
Lower Hybrid Current Drive: ~.8 MA Driven

- System commissioning went very well
  - Up to 2 MW source applied so far from 12 klystrons
    - No signs of power limits or significant arcing on couplers
- Close to 100% of current driven non-inductively in 1 MA plasma
  - Loop voltage 0 or reversed for more than 1 current relaxation time
  - Modeling indicates about .8 MA off-axis current drive from LH
Disruption Mitigation:
Mixed gases give fast response, excellent mitigation

- Mixing small fraction of argon (~10%) with helium yields excellent mitigation and fast gas delivery
- Real-time detection of VDE’s implemented
  - Magnetics used to measure current centroid
  - Digital Plasma Control System used to trigger gas jet when error in vertical position exceeds a threshold
  - Reliable mitigation
Hydrogen Isotope Retention Studies: Significant Retention in All-Metal Walls

- Series of non-disruptive shots
  - Net retention linear in fluence to wall
  - Significantly lower than in carbon machines, but still important for ITER
- Over course of typical day, disruptions lead to net desorption
- No observed difference between pure Mo, and boronized Mo
- Offline laboratory experiments (DIONISOS) show consistent retention results
  - Plasma (ion) bombardment causes lattice damage (vacancies)
- Temperature and exposure history play important roles
  - More work needed to allow better predictions for ITER
ICRF Sheath Enhancement Responsible for Boron Erosion: Important Issue for C-Mod (and ITER?)

- For the equilibrium studied, field lines map from the ICRF antennas to top of outer divertor
- RF sheath-potential enhancement can lead to increased sputtering
- Antennas are on opposite sides of the torus
  - Corresponding field line mapping is to toroidally distinct regions at top of outer divertor
- Conjecture: Boron is preferentially eroded in area with enhanced sheath
  - Supported by energizing different antennas on alternate shots
  - RF erodes boron at least 5 times as fast as ohmic (per joule)
  - Direct sheath potential probe measurements confirm \( V_{\text{sheath}} > 100 \text{V} \)
- Further tests in FY07: marker tiles and thick B-coated Mo tiles installed
Density Peaking at Lower $\nu^*$ Confirmed on C-Mod

- First seen on ASDEX-U
- Possibly important implications for density peaking in ITER
- Low density H-Modes accessed on C-Mod with high-triangularity shape
- Cryopump should allow access to lower density (collisionality) H-Modes in standard shapes
Pedestal Studies Extended over Significantly Broadened Parameter Range

- Extended ranges in current (.4 to 1.7 MA) and magnetic field (2.7 to 8 Tesla)
- Pedestal width insensitive to B, I
- Higher T, lower n (and thus lower $\nu^\ast_{\text{ped}}$) at high B (higher threshold)
- Pedestal pressure independent of B, strongly linked to I (critical gradient), even though not ELMing
- Pedestal density increases with $I_p$
  - $n_e$-ped (and thus core $n_e$) not easily increased by gas-puffing
  - Could be an issue for ITER H-mode scenarios
- Cryopump may shed new light on fueling impact
Studies of Discrete ELMs Reveal new Details of Dynamics

- Hi-frequency magnetic oscillation observed coincident with ELM filament ejection
- Non-thermal ECE emission generated during filament ejection
- Diagnostics include: Ultra-high speed CCD + Gas Puff Imaging (>100kHz); Magnetics; ECE, ICRF Loading Resistance
- ELITE Analysis: ELMing pedestals are close to and sometimes slightly exceed peeling/ballooning instability boundary

Time-Sequence of ELM Perturbations

• Onset of rapid growth of ELM precursor amplitude: ~40 μs before “hi-freq. mag. osc.”
• Onset of (outboard) Te perturbation: ~coincident
• Onset of (outboard) filament ejection: ~coincident
C-Mod Plays Major Role in Education of Next Generation of Fusion Scientists

• Typically have ~25-30 graduate students doing their Ph.D. research on C-Mod
  – Nuclear Science & Engineering, Physics and EECS (MIT)
  – Collaborators also have students utilizing the facility (U. Texas, U.C. Davis, U. Wisc., ASIPP, China)
  – Current total is 30 (27 full-time on-site)
  – Fully involved in all aspects of our research, leading many experiments

• Of 48 C-Mod presentations at 2006 APS-DPP meeting, 27 were presented by students

• MIT undergraduates participate through UROP program
• Host National Undergraduate Fusion Fellows during the summer
Key New Capabilities for FY07

- 3 MW (source) LH power — expect to couple up to 1.5 MW into plasma (Parker presentation)
- Upper divertor cryopump (LaBombard presentation)
  - Particle/density control — conventional H-Mode and AT target scenarios
  - Reduced collisionality regimes — large ELMs, NTM stability, LHCD efficacy
- Tungsten lamella tiles
  - High heat-flux capability; ITER relevant design
Key New/Upgraded Diagnostics for FY07

- Significant new/upgraded diagnostics
  - New imaging x-ray spectrographs (core and edge rotation, T_i profiles)
  - CXRS upgrades — improved coverage and spatial resolution (rotation and T_i, r/a>0.5)
  - Radial correlation reflectometry (fluctuations)
  - Core Thomson scattering upgrade — additional spatial channels (ITB profiles)
  - Upper divertor/cryopump halo rogowskis (toroidal resolution)
  - Gas Puff Imaging — new lower divertor view (edge/divertor fluctuations)
  - Edge magnetics upgrades — increased toroidal mode number resolution) (TAE, NTM, low frequency MHD)
  - New Penning gauges — pressure measurements to assess cryopump
  - Surface Science Station — Includes quartz microbalances for erosion/redeposition, boronization studies
  - Upgrades to bolometers, langmuir probes
  - New shuttered inner-wall retroreflectors for polarimetry prototype
  - Dust injection system
C-Mod Fusion Science and Technology Priorities

- **Plasma Boundary**
  - Turbulence and edge/SOL transport
  - Edge flows and coupling to core rotation
  - Isotope retention and recycling
  - High-Z PFC operational experience, including tungsten tile development

- **Transport**
  - Self-generated flows and momentum transport
  - Role of magnetic shear (enabled by LHCD)
  - Role of collisionality (enhanced by cryopump)
  - Fluctuations and Electron transport
  - Particle and Impurity transport
C-Mod Fusion Science and Technology Priorities (cont’d)

- **Macroscopic Stability**
  - Disruption mitigation (massive gas puff); Disruption database (ITPA)
  - Alfven modes, cascades
  - Sawtooth Stabilization

- **Waves**
  - Lower Hybrid
    - Coupler technology
    - Accessibility
    - Current drive, heating
  - Ion Cyclotron
    - Antenna-Plasma interactions
      - RF coupling
      - Sheath rectification
    - Sawtooth modification
    - Minority $^3$He heating

---

![Graph showing loop voltage reduction versus normalized $P_{LH}$](image)

- Fully non-inductive
- $120 < P_{LH} < 830$ kW
- $n || = 1.6$
- $I_p > 700$ kA
- $\bar{n}_e = 3.5 - 7 \times 10^{19}$ m$^{-3}$

- $P_{LH} / n_e I_p R_0$ (w m$^2$ / $10^{19}$ A)
Research strongly motivated by, aligned with, high priority ITPA/ITER research issues

• Boundary Science
  – SOL plasma interaction with main chamber
  – H isotope (tritium) retention, removal
  – Inter-ELM transport, ⊥ SOL transport
  – Dimensionless cross machine comparisons for SOL physics
• Pedestal
  – Large vs. small ELM regimes
  – Structure: transport and atomic physics
  – Contributions to pedestal database
• Transport physics
  – Reactor relevant conditions (electron heating, equilibrated e-i, low momentum input)
  – Commonality of transport physics in hybrid, s.s. scenarios with reactor relevant conditions
  – Comparisons of turbulence measurements with simulations
• Macrostability
  – Disruption mitigation and disruption database
  – Intermediate-n Alfven Eigenmodes (active antennas)
  – NTM stabilization, Sawtooth stabilization
• Confinement database and modeling
  – Effects of $\nu^*$ vs $n/n_G$, $\beta$ scaling, $\rho^*$ scaling, analysis of ITER reference scenarios
  – Density peaking
• Steady State Operation
  – Qualifying Hybrid scenarios at ITER-relevant parameters
• Diagnostics
  – Dust measurement, erosion
Strong Participation in ITPA Joint Experiments
(High priority for FY07 runtime in red)
(Others had runtime in FY06)

- CDB-4 Confinement scaling in ELMy H-modes: $\beta$ degradation
- CDB-8 $\rho^*$ scaling along an ITER relevant path at both high and low $\beta$
- CDB-9 Density profiles at low collisionality
- TP-6.1 Scaling of spontaneous rotation with no external momentum input
- PEP-7 Pedestal width analysis by dimensionless edge identity experiments
- PEP-10 The radial efflux at the mid-plane and the structure of ELMs
- PEP-16 C-Mod/NSTX/MAST small ELM regime comparison
- DSOL-1 Scaling of type I ELM energy loss
- DSOL-3 Scaling of radial transport
- DSOL-4 Comparison of disruption energy balance in similar discharges and disruption heat flux profile characterization
- DSOL-5 Role of Lyman absorption in the divertor
- DSOL-11 Disruption mitigation experiments
- DSOL-13 Deuterium codeposition with carbon in gaps of PFCs (boron in C-Mod)
- DSOL-15 Inter-machine comparison of blob characteristics
- DSOL-19 Impurity generation mechanism and transport during ELMs for comparable ELMs across devices
- MDC-1 see DSOL-11
- MDC-3 Joint experiments on NTMs (including error field effects)
- MDC-5 Comparison of sawtooth control methods for NTM suppression
- MDC-10 Measurement of damping rate of intermediate toroidal mode number Alfven Eigenmodes
- MDC-12 Non-resonant magnetic braking
- SSO-1.1 Document performance boundaries for steady state target q-profile
- SSO-2.1 Qualifying hybrid scenario at ITER-relevant parameters
- SSO-3 Modulation of actuators to qualify real-time profile control methods for hybrid and steady state scenarios
C-Mod Contributions to Priority ITER Science

• Integrated Scenarios
  – Lower Hybrid Current Drive for Advanced Tokamak scenarios
    • Hybrid scenarios
    • Quasi-steady-state, fully non-inductive
  – Compatibility of high-Z Plasma Facing Components
    • Impurity dynamics; ICRF sheaths
    • Hydrogen isotope retention
  – H-Mode pedestal physics
  – Small and large ELM regimes
  – H-Mode threshold physics
    • Low density limit
C-Mod Contributions to Priority ITER Science

- **Boundary**
  - Erosion, Deposition
  - Isotope retention and removal
  - Radiation transfer in the divertor and effects on detachment
  - Divertor viscosity, atomic and molecular collisions (high neutral density)
  - Cross-field SOL transport, filamentary turbulence

- **Macrostability**
  - Disruption mitigation (including MHD and radiation physics)
  - Error field/locked mode physics
  - Intermediate toroidal mode number Alfven Eigenmodes

- **Transport**
  - Torque-free rotation, momentum transport
  - Density peaking, particle transport, impurity transport
  - Electron transport

- **Wave-Plasma**
  - RF code benchmarking
  - RF coupling (experiment and modeling)
  - Fast wave minority heating (including low single-pass absorption regimes)
  - Mode-conversion heating and current drive
C-Mod Contributions to Priority ITER Technology

• Disruption mitigation (massive gas, mixed gases, real-time detection)
• Tungsten Plasma Facing Components
• Real-time active ICRF matching
• Data system tools
• Remote participation tools
• Wall conditioning/coatings
• Dust dynamics
• Polarimetry (ITER geometry, field, line integral density)
• X-ray spectrograph technology (high count-rate, radiation resistant)
A few examples (not exhaustive - there are ~300 cards):

**ITPA generated:**
- AUX-6 (ITPA SSO) Lower Hybrid Current Drive system for ITER.
- AUX-11 (ITPA CDBM) Required power for H-mode.
- DISR-1 (ITPA SOL) Disruption Mitigation System.
- Shaping-1 (ITPA PED) Optimize Shaping Flexibility.
- FW-2 (ITPA SOL) Change of first wall materials.

**BPO generated:**
- 1.9-15 (BPO MHD, Control) ITER Disruption mitigation system design and physics understanding.
- 1.9-17 (BPO Waves) ICRF antenna performance and coupling.
- 1.9-18 (BPO Int.Scen.) Heating and CD mix on ITER, and impact on achievable scenarios.
- 1.9-20 (BPO Boundary) Tritium retention and H/D/T control.
- 1.9-21 (BPO Boundary) Pedestal and L-H Transition.
- 1.9-22 (BPO MHD) Locked mode and error field correction specification.
2006 PAC Recommendations

- LHCD, cryopump and $j(r)$ measurements are a package; C-Mod should continue aggressive development of these tools
  - LHCD is successfully commissioned and driving current
  - Cryopump is installed and being readied for operation
  - DNB has been rotated to solve a clear MSE issue
  - Polarimetry development continuing (inner wall retro-reflectors, FIR laser)

- Disruption Mitigation: Optimize gas delivery system; Study detection of conditions about to lead to disruption
  - He/Argon mixtures highly effective (fast delivery, strong radiation)
  - Real-time detection and mitigation of VDEs
2006 PAC Recommendations (cont’d)

• **Predictive capability for onset of locked modes due to error fields important for ITER; continue research with emphasis on extending cross-machine comparisons of the threshold.**
  – Joint experiments continued in FY06
  – Extrapolation from C-Mod/JET implies ITER threshold $\delta B/B \sim 10^{-4}$, within design specifications
  – DIII-D non-dimensional identity data did not match C-Mod/JET; still unexplained

• **Efforts to identify localized sources of metal influx are a first step to resolving undesired metal sources in an all-metal machine and are strongly encouraged.**
  – Identified ICRF sheath rectification, at surfaces connected along field lines to antennas, as primary mechanism
  – Now installing metal marker and B-coated tiles
Further characterization of deuterium retention in mixed Mo/B wall is important for projecting T retention in ITER.

- Studies in FY06 indicate that boron does not play a significant role
  - Retention for clean Mo and boron coated similar
  - DIONISOS lab experiments consistent with tokamak studies – understanding beginning to emerge
- Will continue in FY07

PAC suggests that C-Mod explore the possibility of in-situ deposition of boron during a shot.

- 2 experiments: Boron dust injection; Diborane puffing.
- Neither approach led to significant metal mitigation

What are the metrics for successful operation of tungsten tiles?

- W-rods showed some edge-melting (similar to Mo); some pins sheared off
- Lamella tiles installed for FY07
  - Mechanical integrity; Direct comparisons of power handling with Mo; Monitor W in core plasma
  - Plan to push lamellae close to limits with high-power (~5 MW, >1 s)
2006 PAC Recommendations (cont’d)

• Completion of experiments and modeling to understand H isotope retention in Mo, Mo/B, will have important implications for ITER. PAC encourages use of benchmarked codes such as TMAP in modeling efforts.
  – Retention experiments on C-Mod a strong focus in FY06; will continue.
  – Supporting lab. experiments also underway (U. Wisc. and MIT)
  – TMAP does not provide variability of trap density vs. depth, so developed our own code (G. Wright, U. Wisc., D. Whyte, MIT)

• Development of integrated scenario discharges would be strongly aided by 1.5D transport code predictions of profile temporal evolution
  – Modeling with TSC has begun, both of existing discharges, and predictions (Kessel, PPPL) — see Hubbard, Advanced Scenario presentation)

• Low rotation and $T_i=T_e$ provides critical test of models in transport evolution codes; C-Mod has opportunity to study role of magnetic shear and Shafranov shift dependencies in conditions with weak ExB shear.
  – Have extensive modeling and comparisons with gyrokinetic codes (GS2 and gyro) — probably represents best tests of transport understanding (Greenwald, Transport presentation)
• **Would be beneficial to enhance collaborations with outside theoretical capability, particularly in areas where C-Mod has high quality experimental data to challenge the theory/computation efforts. One such area might be edge plasma modeling, particularly for edge transport predictions.**
  
  – Working closely with LLNL theory group, comparing measured and modeled edge turbulence characteristics using BOUT (See recent IAEA paper, submitted to NF: "Theory and Fluid Simulations of Boundary Plasma Fluctuations", R H Cohen, B LaBombard, D D Ryutov, J L Terry, M V Umansky, X Q Xu, S Zweben)
  
  – Through the efforts of Stewart Zweben, also working with Bruce Scott (IPP Garching) to compare experimental results with his GEM code. Dedicated run time in FY06 and more planned for 2007 campaign to enhance this collaboration.

• **Thought should be given to desirability to obtain higher LH power to access high non-inductive regimes.**

  – Implementation of 4th LH cart (4 additional Klystrons) moved up in priority; installation scheduled for FY09 operation
  
  – Redesigning front end waveguide components to reduce RF losses; will be implemented in second launcher, then retrofit first launcher
  
  – Considering additional 1 MW power (beyond 4 MW source); requires incremental funds (~$3/watt)
• Fast wave electron heating via Landau damping at frequencies below 2\textsuperscript{nd} harmonic deuterium, in the vicinity of fundamental deuterium, identified as heating and CD source in reactor studies; C-Mod uniquely capable of exploring this area.
  – We are currently concentrating on scenarios with direct ITER relevance
  – Could explore this regime with 60 MHz, but awaits a critical mass of high priority experiments at this frequency
  – Related proposal (C.K. Phillips) for RF below all cyclotron resonances – 43 MHz, also not in FY07 plan
• Highest priority should be given to commissioning LHCD system in the forthcoming campaign (FY06).
  – Done.
  – Campaign was extended at the end, particularly to allow for additional LH runs (4 out of the final 8 run days)
• Engage expertise within the U.S. fusion community, and possibly beyond, to help resolve outstanding problems with MSE diagnostic.
  – Two meetings organized by S. Scott
    • At PPPL, including PPPL and Nova Photonics experts
    • Satellite meeting at High Temperature Plasma Diagnostics Conference
  – Radial beam injection identified as one key issue; DNB rotated 7\textdegree for FY07 campaign
2006 PAC Recommendations (cont’d)

• *In view of potential implications for ITER and other devices, continued efforts to understand the causes of disintegration of Ti antenna grill are encouraged.*
  – Series of laboratory investigations could not duplicate the C-Mod results
  – May take up additional studies in coming year
• ITER-relevant heating schemes are being studied and there is scope to make major contributions to improved understanding of the interaction of ion cyclotron waves with the plasma edge, impact of parasitic resonances, sawtooth manipulation and possibly other phenomena.
  – Sheath rectification identified as key boron erosion mechanism; possible amelioration approaches being investigated
  – MCCD sawtooth control among highest priority ICRF proposals from Ideas Forum
• *LHCD and ICRF experiments are supported by extensive theory and modeling activities. … It is important that adequate computing facilities are available to fully exploit such developments.*
  – Excellent access to supercomputing clusters at ORNL and NERSC (particularly through SciDAC)
  – Local parallel cluster undergoing significant upgrade, with substantial monetary support from C-Mod
Evolution towards lower collisionality may be accompanied by the appearance of large ELMs. This may pose additional challenges for optimization of [RF] coupling, but also offers another opportunity to address critical issues for ITER.

- Studies begun in FY06 (ICRF)
  - Bench tests of FFT system fast enough to maintain matching through ELMs (R<30%)
- LH coupling through ELMs should be tested in FY07
  - Consider local gas puffing if this is an issue (JET experience)
- Cryopump should significantly expand low collisionality operational space

It is suggested that analysis of gas-jet penetration analysis be applied to DIII-D disruption mitigation data to see if deep gas jet penetration was also unnecessary there.

- Experimental results from DIII-D show that penetration is also not needed for mitigation on that device
- NIMROD modeling for DIII-D, and comparisons with the C-Mod results, are ongoing

We … note that theory could help understand whether the QC mode is actually due to a coupling with a TAE mode.

- Experimental results do not support this hypothesis
  - Many examples of QC with no TAE
  - Nevertheless, we are consulting with Breizman (U. Tx.) to see if there might be a connection in some cases
If extensive further development of the digital control system is contemplated, C-Mod may wish to consider whether it would be more worthwhile to adopt an existing system from elsewhere.

– We entered into discussions with the DIII-D Group concerning adoption of their control system for use at C-Mod. We determined that implementation of this system would not be cost-effective, at least in the near-term. Issues included: ease/cost of implementation and continuing maintenance requirements; compatibility with existing control algorithms; suitability of User Interface; flexibility and ease of modification; incorporation into MDSPlus data structure.

– We will continue to re-evaluate our requirements during the next campaign, and may reconsider our approach at a later time. Communications with the DIII-D control experts remain open.

We suggest expanded efforts to understand transport with divertor detachment, because detachment is required for ITER handling.

– We are working closely with UCSD (A. Pigarov) in comparing measurements of strong parallel flows with models that include a ballooning-like transport ansatz. The dependence (or not) of the flows on divertor detachment conditions is an area of focus.

– The new inner wall 'WASP' probe will provide key data on these phenomena during the upcoming 2007 campaign.
We highly encourage the new efforts focused on RF-related plasma-surface interactions. … If some of these RF-related issues are coupled to transport, SOL transport expertise at C-Mod may help to provide useful understanding of antenna design and operation for ITER.

- A new set of 'marker tiles' will be installed in the 2007 campaign to allow us to further pin down ICRF-enhanced sputtering erosion of the boron layer on the shelf of the outer divertor modules
  - Thick boron-coated tiles will be tested as possible solution for C-Mod
  - An X-mode edge reflectometry system is being built (with ORNL) to measure density profiles in front of one of the C-Mod ICRF antennas.

(Spontaneous rotation): … the study of … coupling of SOL flows through the pedestal to the core is unique and of great scientific interest and should be pursued. As recognized by the team, it is crucial to have measurements of toroidal rotation over the outer third of the plasma and we support the multiple efforts being pursued to make these measurements.

- CXRS measurements for edge rotation profiles working in FY06; more views/spectrometers being added in FY07 for increased radial coverage and resolution (toroidal and poloidal)
- 2 new high resolution imaging x-ray spectrometers for \( V_\phi \) and \( V_\theta \) — coverage: \( 0<r/a<0.8 \) (H- and He-like argon) and \( 0.8<r/a<0.95 \) (He-like neon)

Also, we encourage theoretical work to explain this phenomenon (spontaneous rotation).

- Active collaborations with Coppi, Ernst, Catto, Freidberg (MIT), Diamond, Gurcan (UCSD), C.S. Chang (NYU)
We encourage work to extend these [pedestal] studies to the width of the electron temperature pedestal. Critical gradient ideas that were presented ... are another obvious direction to pursue.

- Pedestal scaling studies (extended to high field and reversed-field discharges in 2006) show qualitatively similar behavior for electron density and temperature pedestals
- Empirical evidence for critical pedestal pressure gradient extended to regimes of lower edge collisionality
- 2007 plans include using improved ion temperature diagnostics to look at ion pedestals, the study of profile gradient behavior with applied cryopumping, and understanding the role of edge magnetic shear in determining the pedestal width

[ongoing] inter-machine comparisons might be one of the best levers to gain insight into the scaling of pedestal width and other properties.

- Have obtained H-modes in discharges suitable for non-dimensional pedestal match with JET (IEA/ITPA joint experiment PEP-7); awaiting follow-up experiment from JET
- Started experiments intended to match dimensionless pedestal quantities on NSTX for comparisons of small ELMy regimes (PEP-16); near-term work will revisit this experiment with increased pedestal pressure, density scan
We encourage studies to determine if the peeling-ballooning linear theory of ELMs is consistent with the observed onset of the discrete ELMs in C-Mod. Also, studies of the transition between the ELMing and neighboring non-ELMing regimes would be of interest and might provide some insight into why discrete ELMs are generally not observed in C-Mod. Fast diagnostics, particularly the fast cameras, can be used to study the structure of the ELM instability during its non-linear phase and results compared to those from other machines.

- Extensive work in this area in FY06, culminating in invited talk at APS (J. Terry) and associated publication.
- Analyses of the C-Mod edge in the discrete ELM regime with ELITE (the linear peeling/ballooning MHD code) are consistent with the observed boundary for ELM onset; Analyses using the resistive-MHD code M3D have also been done.
- C-Mod is currently involved with the ITPA Research Task studying the structure and dynamics of ELMs.
- 2 proposals for studying ELM structure, dynamics, and stability have been assigned "high priority" status for the upcoming campaign.
- Cryopump should give expanded access to low $\nu^*$ regimes, and possibly large ELMs over more of our operational space.
Priorities for Major Upgrades (FY07-09)

- Polarimeter/Interferometer (tests now, full system FY08)
  - Current density profiles over entire range of $n_e$ operation
- New x-ray spectrographs (with PPPL) high throughput, high spatial resolution (install FY07)
- New 4-strap ICRF antenna (fab FY07-08, operate FY09)
  - Maintain full ICRF capability with addition of second LH launcher
- Second Lower Hybrid Launcher (fab FY07-08, operate FY09)
- Install 4th MW Lower Hybrid Source Power (fab FY07-08, operate FY09)
  - Full non-inductive regimes
- Core Thomson upgrade (8 additional channels) (install FY07)
  - Better spatial resolution (especially for ITB discharges)
- Computing Cluster upgrade (FY07)
- Upgrade outer divertor (advanced material)* (FY09)
  - Improved power handling for 5 second pulses
- Real-time matching – final 3 transmitters* (FY08-09)
- Spare Klystrons* (FY08-09)
- Additional MW LH source power, to 5MW total* (FY09-10) – if required for fully non-inductive AT regimes

*Require incremental funding
## Budget Profiles (k$)
(no guidance yet for FY08)

<table>
<thead>
<tr>
<th>Institution</th>
<th>FY06 (appropriated)</th>
<th>FY07 (guidance)</th>
<th>FY08 (flat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT</td>
<td>19,350-128</td>
<td>19,703+128</td>
<td>19,703</td>
</tr>
<tr>
<td>PPPL</td>
<td>1,993+128</td>
<td>1,994-128</td>
<td>1,994</td>
</tr>
<tr>
<td>U Texas</td>
<td>410</td>
<td>413</td>
<td>413</td>
</tr>
<tr>
<td>LANL</td>
<td>99</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>National Project Total</td>
<td>21,852</td>
<td>22,210</td>
<td>22,210</td>
</tr>
<tr>
<td>(research run weeks)</td>
<td>Target:14 Achieved:16.7</td>
<td>Target:15</td>
<td>Target:13</td>
</tr>
<tr>
<td><strong>5 Year Proposal</strong></td>
<td><strong>28,710</strong></td>
<td><strong>29,450</strong></td>
<td><strong>29,887</strong></td>
</tr>
<tr>
<td>(research run weeks)</td>
<td>(25)</td>
<td>(25)</td>
<td>(25)</td>
</tr>
</tbody>
</table>
Incremental Funds (~10%) Would Significantly Improve Progress

• Facility Operation: 4 additional run weeks [$800k]
  – Currently only about 1/3 of priority runs can be accommodated
• Significantly earlier implementation of key upgrades
  – Outer divertor (advanced material) [$375k*2]
• Increased reliability, increased utilization
  – Spare Klystrons [$500k*2]
Top Level Program Milestones FY07-FY08

• FY07
  – JOULE milestone: Operate facility for 15 (±10%) research run weeks
    • Assumes guidance budgets
  – Investigate particle and density control with the new upper divertor cryopump
  – Investigate Lower Hybrid RF in L- and H-Mode plasmas, including study of combined Lower Hybrid RF and Ion Cyclotron RF
• FY08 (anticipated)
  – JOULE milestone: Operate facility for n (±10%) research run weeks
  – JOULE milestone: Rotation physics (joint with DIII-D and NSTX)
**FY07 Run Prioritization**

All Areas Significantly Oversubscribed

- Ideas Forum (December, 2006) [Hughes presentation]
- Follow-up task group meetings to prioritize with tasks
- Experimental Program Comm. examining overall balance [Wolfe]
- Initial draft allocations (60 total research run days)*:

<table>
<thead>
<tr>
<th>Category</th>
<th>Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operations</td>
<td>6</td>
</tr>
<tr>
<td>Diagnostic Development</td>
<td>4</td>
</tr>
<tr>
<td>Divertor/Edge</td>
<td>6</td>
</tr>
<tr>
<td>Transport</td>
<td>10</td>
</tr>
<tr>
<td>Macrostability</td>
<td>6</td>
</tr>
<tr>
<td>Lower Hybrid</td>
<td>9</td>
</tr>
<tr>
<td>ICRF</td>
<td>6</td>
</tr>
<tr>
<td>Integrated Scenarios: H-Mode</td>
<td>6</td>
</tr>
<tr>
<td>Integrated Scenarios: Advanced Scenarios</td>
<td>7</td>
</tr>
</tbody>
</table>

*Does not include start-up runs (~14) or piggy-backing
5-Year Proposal (Nov 2008 – Oct 2013)
Possible Directions for Emphasis

• Cross-Cutting Themes
  – Fully non-inductive long pulse AT up to the no-wall \( \beta \) limit
    • Integrated current drive, heating, MHD, transport, power handling
  – Plasma-Material Interactions and First Wall for steady-state
    • Wall material(s), conditioning, ICRF sheaths, erosion/redeposition, tritium retention, power handling, off-normal events

• Science Focus Areas
  – Torque-free rotation — what is the underlying physics?
    • Fluctuations, theory
  – First-principles understanding of scrape-off layer turbulence-driven transport
  – Develop RF actuators for plasma control of advanced tokamak operation
    • validate wave propagation, power deposition, and current drive calculations with self consistent distribution functions for electrons and multiple ion species
  – Energetic particle driven instabilities and implications for \( \alpha \)-heating

• Proposal Schedule
  – Planning (now through ~December)
  – National Tokamak Workshop (at MIT, Sept 17-19, 2007)
  – PAC review of detailed plans (January, 2008)
  – Proposal for peer review due to DoE (April, 2008)
Summary

- Unique dimensional regimes
- ITER relevant heating and current drive tools, metal PFCs
- Strong, broad contributions to high priority ITPA/ITER research
- Exciting prospects in coming 3 years with new tools and diagnostics
  - LHCD; cryopump
  - Disruption mitigation
  - Turbulence measurements
  - X-Ray spectrographs, CXRS upgrades
  - Surface Science Station; QMB deposition monitors
  - Langmuir probe upgrades
- Tight coupling to theory and modeling
PAC Members - 2007

• Rich Groebner, General Atomics (Chair)
• Chuck Kessel, PPPL
• Brian Lloyd, UKAEA, Culham
• Alberto Loarte, EFDA, Garching
• Dale Meade, PPPL (retired)
• Craig Petty, General Atomics
• Paul Terry, U. Wisconsin-Madison
• Jim Van Dam, U. Texas-Austin

• Adam Rosenberg, OFES (ex-officio)