Report of the DIII-D Program Advisory Committee Meeting
February 15-17, 2005

1. Introduction

The DIII-D Program Advisory Committee met at General Atomics on February 15-17, 2005 and was asked to respond to the following two charges:

CHARGE #1 ***REVIEW LONG TORUS OPENING FACILITY ENHANCEMENTS AND THEIR ROLE IN THE DIII-D LONG RANGE RESEARCH***

The DIII-D Program is about to enter into a Long Torus Opening of one-year duration in which several major facility enhancements will be implemented. We invite your views on the current status of the LTO Activities and on how best to use these new capabilities for the high leverage research elements that we plan to carry out in the years following the completion of the LTOA. These enhanced capabilities and the research program which capitalizes on them will enable advances in fusion science critical to ITER and the progress of fusion generally.

CHARGE #2 ***THE RELATION OF THE DIII-D PROGRAM AND ITER***

The DIII-D research program and the resources of the DIII-D facility must become increasingly coupled with ITER. We invite your comments on how we see these couplings evolving over the next few years. We will seek to be as explicit as possible on various aspects of DIII-D research that are rather specifically tied to ITER and various aspects of the DIII-D facility capabilities that will interact with the ITER program. We seek your comments on whether we have chosen the appropriate areas for focus based on their importance, our capabilities, the uniqueness of the opportunity, and the relation of our work to that of other experiments worldwide.

As has been the case in past years, the presentations were well prepared and, perhaps even more than in past years, were well formulated to help the committee address the charges. The PAC especially appreciated the thorough response to last year's report as presented by T. Taylor.

The PAC congratulates the DIII-D team on its outstanding achievements in the past year, a few highlights of which include:

Impressive progress on the development of an advanced Plasma Control System (PCS), including a new NTM control algorithm that maintains island and ECCD alignment through real-time q-profile reconstruction;

Achievement of discharge regimes demonstrating parameters that when projected to ITER could result in 1) fusion powers as high as 700 MW with the possibility of ignition, 2) a fusion gain of Q ~ 10 for a flattop time of 3900 s and 3) steady-state operation with Q ~ 5;

Feedback stabilization of RWMs in low rotation plasmas with internal control coils and high-bandwidth amplifiers;

A vigorous reentry into the area of fast-particle physics with elegant diagnostics that allow clear identification of internal Alfvén Eigenmodes including the observation and interpretation of the "sea of AEs" in AT plasmas;

Continued progress in the theoretical and experimental identification of mechanisms of anomalous transport, and mitigation, with improved diagnostics spanning the range $0.1 \leq k_{\perp}\rho_s \leq 10$ for density fluctuations;

ELM suppression using n=3 resonant magnetic perturbations;

First measurements of the edge current density with the Lithium beam, permitting more detailed assessment of MHD stability in the vicinity of the pedestal;

Measurements of the migration of C13 showing the poloidal flow of hydrocarbons and deposition near the divertor strikepoint;

Installation of 3 MW of high-harmonic fast wave power at 60, 110 and 115 MHz together with two new antennas and successful coupling of 2.7 MW for ~ 1 s into an L-mode plasma with measurable increase in neutron emission, an impressive accomplishment at this early stage of operation.

Clearly, the DIII-D team has had a very productive year with a good balance of results contributing both to progress in basic fusion science and the physics R&D support of ITER.

2. The Budget Situation

Just prior to its meeting, the FY 2006 Presidential Budget was made public and the PAC was informed that the 2006 budget projection for DIII-D is about 10% lower than the 2005 level. While a complete assessment of the impact was not available, it is clear that a cut this deep would lead to a loss of personnel, limit the scope of the Long Torus Opening Activities, reduce 2006 run time and permit only a minimal deployment of new diagnostics for the restart of operations. The PAC regrets this situation and would like to stress that the DIII-D program is making important contributions both to fusion science as well as the design of ITER and the preparation of its operating program. Furthermore, DIII-D is equipped to make *unique* contributions in the future that will be vital to ITER's success. In the PAC's judgment, further experimentation on DIII-D is essential for maximizing the prospects of success for ITER, as well as for charting a path to an attractive reactor, and the PAC therefore registers its strong concern over the impact of the potential budget cut on the DIII-D program's productivity.

3. General Response to the Charge

3.1 *The Long Torus Opening Facility Enhancements and Their Role in the DIII-D Long Range Research*

The DIII-D team presented a near-term plan to the PAC that calls for an extended machine opening beginning in April 2005 and continuing for about one year with operations resuming in April, 2006. During this time, the following upgrades and modifications would be implemented:

- Procurement and installation of 3 additional CPI 1 MW gyrotrons, with pulse length of 10 s and frequency of 110 GHz.

- Rotation of one of the 2-source beamlines

- Lower divertor modification

In parallel, the PAC was informed that some work on a TF upgrade, which has a long range goal of 10 s pulse capability, would also be carried out, at lower priority and with a scope that will depend on the FY2006 budget.

The gyrotron procurement will increase the total ECH/ECCD source power to 6 MW, with up to 4 MW coupled to the plasma, at a pulse length of 10 s. This will permit an extension of NTM stabilization experiments in both pulse duration and power, and increase the ECCD capability for development of AT modes.

In previous years, the PAC has recommended rotating a beamline and we continue to believe that this is a high value modification. As will be evident in several of the following sections, rotating a beamline will enable a rich array of new physics investigations, for example, untangling the interplay between effects due to driving current vs rotation. We note however that this comes at the price of less NB current drive power.

The lower divertor modification will allow more strongly shaped plasmas with density control assisted by the lower divertor pump. This will be important to maintain the efficiency of ECCD in steady-state scenarios with high bootstrap fraction and higher heat throughput.

The PAC agrees that extension of the DIII-D pulse length to 10 s should be lower in priority relative to the three activities listed above, however, it would seem sensible during the LTOA to improve cooling of those TF beltbus areas that would require an extensive vent, while postponing those 10 s pulse length extension tasks that can be done without a long shutdown.

The present FW capability together with a possible upgrade to the 5-6 MW level would provide an important new tool in the pursuit of DIII-D’s AT program goals. The PAC understands however that the FW upgrade will depend largely on the budgets of its collaborators, in this case ORNL and PPPL.

Finally, the PAC recognizes that the first priority in the LTOA must be given to the three major items listed above. However, we emphasize that it is important not to neglect diagnostic capability. The PAC was pleased to learn that essentially all diagnostics displaced by the beamline rotation would be restored during the LTOA, and that some divertor diagnostics will be improved. The PAC urges that high priority be given to installing important new diagnostics, for example completion of the MSE sightlines and D_α fast ion spectroscopy.

In summary, the PAC fully endorses the LTOA plan as it was presented. When operation resumes in April 2006, a rich array of new tools should be available and thus ensure DIII-D’s continued leadership and prominence in the world fusion program. The anticipated results from the physics program permitted by these modifications will be valuable to both the design and operation of ITER, as well as to the development of the physics basis of an attractive reactor.

3.2 *The Relation of the DIII-D Program and ITER*

The DIII-D team has done an excellent job in showing in their presentations how their research relates to ITER needs. DIII-D is clearly among the world leaders in providing support to the ITER physics design. In particular the work on confinement physics and the development of AT discharges is outstanding and has high relevance for ITER. Also, the progress in transport modelling and in the understanding of ELMs is highly ITER relevant, even more so as predictions to ITER become possible.

In general the comprehensive coverage of tokamak physics in theory and experiment is an outstanding feature of the DIII-D program and is an important element in supporting the ITER physics basis. The PAC commends the DIII-D team for its strong participation in the ITPA process and encourages its continuation. The PAC also encourages the DIII-D team to perform ITER Physics Tasks defined by the ITER-IT. This will allow ITER to take advantage of the experimental and modelling results and further enhance DIII-D's contribution to ITER.

Joint experiments with other machines are very important to understand the scaling of the main physics issues. The PAC recommends that, even with tight budgets, sufficient funding be made available for DIII-D team members to participate in similarity experiments performed in other machines.

From an ITER perspective, the PAC reconfirms the high priority for changing one beamline to counter injection as well as for augmenting the ECH/ECCD power and the divertor modification. In particular the DIII-D experimental work on confinement in inductive as well as in steady state scenarios with low momentum input will be very relevant for ITER. Since DIII-D and JT-60U will be the only machines with balanced injection capability and since little data exist, this area of research is of utmost importance for ITER and complements the studies of rotation without NBI in Alcator C-Mod and JET.

The addition of audio amplifiers will enhance the stabilization capability for RWM, which in connection with low momentum input will be very ITER relevant. It is essential that sufficient amplifiers be made available to test whether feedback stabilization of RWM is as effective as rotation and to assess the implications for ITER. The control of ELMs through application of external fields is an exciting development and improvements to the I-coil power supplies will be important in obtaining predictive capability. Although not foreseen until the latter part of this decade, increasing the pulse length to 10 s (both machine *and* heating and current drive systems) will be important for extending the pulse length of AT regimes well beyond the current diffusion time scale.

The carbon migration work including the studies of an off-site oxygen bake is an important contribution to the choice of first wall materials in ITER. An O2 bake of DIII-D followed by a period of recovery to normal discharges before the beginning of the LTOA would be an important contribution to ITER and the PAC recommends that this possibility be reconsidered. Divertor and SOL modeling including the effects of drifts and carbon co-deposition should be continued with high priority.

Characterization of disruptions, their prediction and mitigation continue to be crucial for ITER design. Recent fast current quench data from DIII-D need more analysis as well as extension to higher pressure machines and this work should be closely coordinated with the ITER IT.

The work on confinement, both experimental and theoretical, is certainly among the best worldwide including also the diagnostic capability. The modelling effort in the various areas of physics (MHD, heating and current drive, SOL and divertor) is also world class. However, the thrust towards a model covering the plasma from the divertor plate to the plasma center is lacking. While the PAC understands that for some areas (e.g., the pedestal) the first principle physics understanding is incomplete, it is of the opinion that a staged approach (e.g., using partially empirical models for the pedestal) to a model would have a large added value. In this context simple scaling predictions towards ITER based on beta and H-factor are very crude and could be misleading. A model even with some empirical elements would be more relevant if validated with the well-diagnosed DIII-D database.

The development of AT discharges has great relevance for ITER and provides the optimism that ITER may even exceed its goals. However, a straight extrapolation of these discharges to ITER is unreliable. Uncertainty exists because, for example, the experiments are based on ion-dominant heating whereas in ITER the heating is electron dominated. The relevance of these scenarios is expected to improve with upgraded ECH and FW electron heating. Comparisons with similar scenarios in larger machines such as JET and JT-60U are an important step to gain confidence that regimes developed on DIII-D can extrapolate to ITER.

4. Comments on Topical Area Presentations

4.0 *Toward Steady-State Performance*

The PAC is pleased to note significant progress on steady state scenarios, including achieving stationary conditions that may project to ITER plasmas that meet ITER's goals at modest bootstrap current levels. The PAC also takes note of transient 'existence proof' plasmas produced for higher-bootstrap current scenarios, and look forward to extension of these results to time scales beyond the resistive diffusion time, made possible by DIII-D long pulse operation. There has been good coordination with the worldwide program in developing and validating the ITER 'hybrid' scenario.

The goal of preparing sustainable, high performance "AT" plasma scenarios for next generation experiments is appropriate. To achieve this goal, it will be necessary to integrate additional aspects into the configuration design, in particular:

- to demonstrate that the AT scenarios can be compatible with steady-state divertor operation in the future experiments.
- to consider fast-ion instabilities and their effects, including fast-ion transport and loss, and scaling of the fast ion instabilities.
- to ensure that the high performance can be sustained in regimes with $T_e = T_i$.

There is a need to assess the importance of plasma rotation in the transport and stability of the steady-state plasmas, and the extrapolation of these scenarios to ITER. This should be a high priority after the counter-NB becomes available.

4.1 *Plasma Control*

The PAC was impressed with the progress on the Plasma Control System (PCS). Especially impressive is the control achieved of NTM modes. An integrated simulation system including models of the plasma response, actuators, diagnostics and power supplies is the right goal and should allow the possibility of stable plasma operation near the limit of the operational regimes.

In the near term, advanced integrated control using well organized diagnostics and many actuators will enhance DIII-D performance, operational flexibility and efficiency. There is a close collaboration with JET where advanced integrated techniques are used for profile control, and joint participation in experiments is planned. In the future, an advanced control system such as the PCS can contribute to other present- and next-generation devices, especially ITER. Other experiments such as ASDEX UG are also developing advanced control systems. It would be worthwhile to coordinate these activities through one of the ITPA groups so that an advanced control system could be specifically developed for ITER.

The results of disruption mitigation by massive gas jet with appropriate diagnostics (how gas jet penetrates into plasma) are welcome. The PAC recommends continuing this work via collaborations between C-Mod, JET and JT-60U to determine its effectiveness for ITER.

4.2 *Resistive Wall Mode (and NTM Physics)*

The DIII-D program has historically been a world leader in MHD stability research on high beta plasmas. The program is known for producing practical, well-defined multi-year plans for MHD stabilization, leading to research success. Two of the major beta-limiting instabilities in tokamaks, the resistive wall mode (RWM) and the neoclassical tearing mode (NTM), continue to be addressed, and results from both of these areas were shown.

Research in the area of RWM stabilization is world-class and has clear and direct ties with other programs including JET. The application of the research toward developing a routine system for active RWM stabilization in low rotation target plasmas has just begun. The program continues to implement planned stabilization system upgrades, most recently including the addition of audio amplifiers for greater system bandwidth to stabilize the RWM up to the ideal MHD with-wall beta limit. This research is critical to future tokamak devices that plan to operate above the MHD no-wall beta limit and especially for such plasmas that are rotating below the RWM critical rotation frequency. Advanced operating regimes in burning plasmas devices such as ITER are expected to have insufficient rotation for RWM stabilization and so could make use of this research. The re-orientation of one neutral beam line during the LTOA should significantly aid this research. One concern is that the available balanced NBI power appears marginal to decouple rotation vs. direct feedback stabilization effects in future active RWM stabilization experiments. The group should clarify how these effects will be decoupled if the balanced P_{NBI} is insufficient. The group should be careful in a tight budget environment to ensure that key supporting diagnostics, such as the new, second MSE position, are given proper priority to support these experiments without undue delay after the LTOA. Schematic plans for research through 2009 were given and the hardware upgrades were also shown. There is at present uncertainty in the need for an upgrade to 24 audio amplifiers in 2007, and it was indicated that the subject was under discussion. This should be a low-cost action item, but the criteria for adding the extra amplifiers and the decision point should be defined on the research timeline.

Arguments were presented on why reversed-shear scenarios are less interesting than low/flat-shear scenarios. The PAC suggests using one of these integrated advanced scenarios as the motivation for RWM stabilization instead of the ARIES-AT scenario

The PAC regrets not having received an integrated presentation of the plans for continued NTM stabilization research, which is also critical to sustained high beta operation in DIII-D and has had great success. In the spirit of the DIII-D program’s past ability to clearly define directed MHD stabilization plans, the program should continue to define this effort for NTMs through the LTOA period and once the machine begins operation after the LTOA. Stating these plans in a manner similar to the statement for RWM stabilization would be effective for this purpose. Also, any known issues with the simultaneous operation of the RWM and NTM stabilization systems should be clearly identified.

There should be sufficient new data for analysis during the LTOA to occupy the MHD research staff. In addition to analysis and tool development efforts performed during this period, the staff should use this unique opportunity to collaborate with colleagues at other institutions in their research interest. There appears to be a plan to organize this research effort.

4. 3 *Energetic Particle Physics*

TAEs were experimentally co-discovered on DIII-D (this work was awarded an Excellence Prize at last year's APS/DPP Meeting) — but subsequently DIII-D almost dropped out of this area of research, in favor of pursuing high beta. Now apparently they're back in the energetic particle business, for which they are to be applauded, since DIII-D has strong capabilities for fast particle research studies. The chart comparing AE capabilities of DIII-D with C-Mod, NSTX, JET, and JT-60U was helpful.

New diagnostics are now available on DIII-D for internal fluctuation measurements: interferometer, FIR, BES, and phase contrast imaging. External magnetic coils have difficulty seeing higher frequency Alfvén modes like Cascades and CAE. The high-resolution FIR observations of "sea of Alfvén modes" with moderate-to-high mode numbers are impressive. Also, the new D_{α} diagnostic seems very promising for measurements of the fast-particle distribution. This diagnostic looks like it could mitigate the loss of the charge exchange diagnostic, which will be a casualty of the Long Torus Opening.

It is exciting that DIII-D plans to address the challenging issues of anomalous fast-ion diffusion, nonlinear saturation of Alfvén modes (especially with multiple toroidal modes), and sustainment of monster sawteeth. With Cascades or high-frequency CAE modes, there has been no evidence yet of fast ion loss; however, redistribution of the fast ions can have significant implications for current drive and heating efficiency. Also, the Cascades can be useful as an internal diagnostic for the q_{min} value in AT operation. The emphasis on the validating of theory is highly commendable. The ongoing theoretical studies with the ORBIT-RF code of the interaction of NB and RF energetic ions with fast Alfvén waves are to be encouraged.

The PAC is pleased that DIII-D is again emphasizing this research area, consistent with its recommendations last year, which also commended development of the D_{α} diagnostic and similarity experiments with NSTX. The PAC continues to believe that performing similarity experiments is a smart idea. Regrettably, due to budget pressure, the 30 MHz ICRH had to be foregone, but the PAC notes that first results from the high harmonic fast wave interactions with the beam are promising.

4.4 *Confinement Physics*

The DIII-D program has continued to make major contributions to the fundamental understanding of plasma confinement by exercising a strong coupling between theory and experiment. The breadth of the confinement studies is also extremely strong. New BES capabilities for measuring high k fluctuations promises to further strengthen the understanding of electron transport, which is one of the areas of primary focus. Balanced beam injection will add new capabilities for understanding and influencing plasma rotation, which will allow new investigations into examining its role in many aspects of plasma confinement.

Because the density profile plays such a strong role in governing turbulence as well as fusion production in a burning plasma, particularly in advance scenarios with reduced core transport, the fusion program would benefit from a stronger integration of particle transport studies with other aspects of confinement in DIII-D. Particle transport is presently considered a secondary emphasis in the DIII-D program as well as in most of the world program. There are several readily identifiable examples of DIII-D capabilities that will enhance its contributions to understanding confinement: 1) build on the turbulent particle fluxes measured by BES to develop a better understanding of local particle transport, 2) exercise the higher power RF capabilities in the future program along with 100% noninductive CD to make a more definitive statement about particle transport in the absence of internal sources and the Ware pinch, and 3) clarify the dependence of all transport channels on Mach number and examine the implications for ITER and future devices.

4.5 *Pedestal Physics*

The DIII-D team continues to make key contributions in the critical area of pedestal physics. An important effort is underway to determine the physical mode responsible for "ELM" activity. When more positively identified, modification or control of the instabilities responsible for ELMs should be addressed in the future in an analogous fashion to the way the DIII-D program is presently addressing RWMs and NTMs. This appears to be a long-term goal of the Pedestal Group, which is to be encouraged. In particular, the team is pioneering the control of ELMs by ergodic fields, a technique of great interest for ITER. The range of shape and parameters for such control has been expanded. The PAC recommends that the technique be assessed at lower ν^* and q_{95}, and its physical mechanism be clarified through both experiments and modeling.

The team continues to be a world leader in pedestal stability analysis. Analysis of peeling-ballooning stability in the QH regime has increased understanding, and modeling of fast time scale ELM crash dynamics is beginning with several models. For the future, the PAC encourages modelling of the Edge Harmonic Oscillation and other fluctuations, which apparently cause the transport in this regime. Experiments using the re-oriented beams to clarify the role of rotation will be key both to understanding the physics and for extrapolating to other experiments. An extensive set of pedestal diagnostics has been used to make detailed profile measurements in many experiments, including ITPA inter-machine comparisons and recently VH modes. The PAC endorses the plan to use the LTOA period to add these data to a new pedestal profile database to facilitate comparison with models. We applaud the implementation of the unique Lithium beam technique for edge j(r) measurements, and encourage its increased use under a wider range of conditions, to test models of the bootstrap current and to clarify its role in ELM physics. Higher time resolution pedestal diagnostics will be needed to pursue the study of ELM dynamics; the priority and timing of these was not made clear.

The close connection with theory groups at GA, LLNL and elsewhere is a strength of the DIII-D pedestal program. While the PAC encourages efforts to extend GLF23 to the boundary, the PAC agrees that this effort needs to be accompanied by more fundamental models; prediction of density as well as temperature pedestals is important. In general, it is important to maintain high priority and visibility for the pedestal thrust and in particular to incorporate this work in the development of advanced scenarios.

4.6 *Boundary Physics*

The DIII-D program is an important contributor to international boundary physics. The recent measurements of ELM fluxes to the 'wall' are some of the first in this area. The C13 migration experiments are a fertile source of data for understanding flows and material migration. The new analysis of camera images serves as an important constraint to UEDGE modeling of core fueling and wall interaction. The upcoming wall gap experiments and radial transport experiments with H-mode plasmas will also contribute valuable information on steady state wall fluxes. The emphases of the past year are excellent and should be continued.

The group presented a good plan for transition to the new lower divertor. All diagnostics will be reimplemented and the extended LTOA down time will be used effectively to upgade them. The replacement of divertor CXRS flow measurements with tangential divertor fiber views makes sense.

The suggested inner divertor modification (smoothing tiles and new probes) has large leverage - little work but substantial enhancement of diagnostics – and the PAC recommends that it be done. It will mean good inner divertor measurements of plasma characteristics (using probes), as well as spectroscopic views (influxes of hydrogenic and impurity components). The idea of making neutral pressure measurements at multiple points poloidally is good. The Penning gauges are cheap and easy, and could give important information on core fueling (and pedestal characteristics), wall recycling, and data for constraining UEDGE. Additional probe measurements on the various baffles at the entrance to the upper and lower divertors would be very helpful in making sense of main chamber fluxes.

There is a program in place to measure wall fluxes (heat and particle) with emphasis on ELMs and steady state (through window frame technique). The PAC recommends expanding such wall flux measurements to include disruptions.

There is a general concern that the compatibility of AT scenarios with divertor operation is not receiving enough attention. The PAC suggests more emphasis in the program including run time.

The PAC was puzzled by the DIII-D position on O_2 bake. There did not seem to be any argument against doing it in the vessel as opposed to the laboratory. As mentioned above, the PAC recommends that it be reconsidered. It should probably be done at ITER wall temperatures with efforts to run a set of plasmas after minimal cleanup (e.g. some number of hours of glow discharge cleaning.)

4.7 *Theory and Modelling Resources for ITER*

Producing validated, predictive models is one of the long-term goals of the US fusion program. The GA and LLNL theory groups are world leaders in a wide range of first principle and theory-based models and the DIII-D Team is committed to the validation of models against DIII-D experimental data. This work is well-focused to the specific needs of the DIII-D program and ITER, is of uniformly high quality and is to be commended highly. The PAC strongly encourages the continuation of this effort, which focuses well the theory/modeling community within the US and leads to a good interaction with the fusion community worldwide.

The PAC applauds the fact that most of the presentations paid significant attention to theory, modeling and comparison with experiment. During the last year, there has been important work to characterize and reproduce turbulent transport and to improve theory-based transport models; to model, understand and control MHD instabilities (including NTM control with ECCD, linear and non-linear development of ELMs, RWMs with the low rotation expected on DIII-D with balanced NBI and on ITER); and to develop and validate models of the edge plasma (including steep profiles in the pedestal region, high flows in the SOL, and 2-D recycling and impurity sources).The PAC encourages the development of synthetic diagnostics to further facilitate comparisons with experimental measurements.

The PAC encourages the further development of an hierarchy of models with differing complexity to demonstrate the depth of understanding, to allow early results from integrated modeling, to progress the development of a tokamak simulator using model-based control algorithms, and to use for the prediction of ITER operating scenarios and the definition of ITER auxiliaries.

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