SUMMARY REPORT

Workshop on the Physics Requirements for Advanced Tokamaks

Held at
General Atomics
San Diego, California

March 9–11, 1999

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July 7, 1999

I. Introduction

A workshop was held at General Atomics on March 9–11, 1999, aimed at determining the physics requirements of an Advanced Tokamak (AT). The goal was to examine the status and direction of Advanced Tokamak research in the U.S., given developments in the last few years in which projections of high β and good bootstrap alignment were made for specific current and pressure profile. Attempts to achieve these states experimentally resulted in the discovery of enhanced core confinement regimes, has motivated recent plans to bring external current drive systems on-line in the DIII–D and Alcator C–Mod tokamaks. The meeting consisted of invited and contributed participation from within the U.S. community, as well as invited participation from the Japanese and European tokamak research efforts.

The origins of the concept of an Advanced Tokamak can be traced back nearly twenty years. Development of the concept was accelerated by work early in this decade which established the possibility of developing a plasma regime characterized by very high β, with stability improvements using flexible plasma shaping coupled with optimized current profiles. The emerging AT concept incorporated the important and oft-stated goal of demonstrating the feasibility of steady-state operation. Research to this end emphasizes the development of external current drive systems, and ultimately aims to take advantage of high bootstrap current fractions that are offered by the appropriate pressure profiles if they can be achieved.

Recently, enhanced core confinement regimes have been a focus of research worldwide and have been cited as one possible basis for AT high β operation. With neoclassical transport being realized in the tokamak core, and since a fundamental understanding of the origins of anomalous transport appears to be emerging, a shift in much of the community’s thinking has been taking place. Indeed, the prospect that transport might be controlled, as opposed to being merely contended with, has wide-ranging implications for any version of a tokamak reactor. It is also clear that a reactor or burning plasma experiment, even if not operated in steady-state, might also benefit from such research.

However, these enhanced confinement modes come with both the promise and burden of the physics of steep pressure gradients. When transport barriers are left to evolve according to their own dynamics without intervention in present experiments, these gradients challenge local stability limits. However, the prospect of control of the steep gradients associated with transport barriers and their location may relieve demands on external current drive systems. This is a consequence of the large bootstrap current fractions that accompany these barriers: in fact, the most significant amounts of non-inductively driven current in tokamak experiments to date have come through the bootstrap effect. Thus AT research has become a stimulating arena in which several major aspects of core physics research — transport and transport control, current drive physics, and stability — must be confronted in a unified manner.

II. Workshop Aims and Structure

Prior to the meeting, a charge was issued to the participants specifying questions aimed to generate focused discussions on future research directions (see Appendix I).

The charge specified some general questions as well as several detailed technical issues and talks were requested to address both. The general charge was as follows:

1. Provide a description of your vision of an Advanced tokamak reactor.
2. Describe efforts to connect this long-range goal with near-term experiments and modeling.
3. Discuss issues pertaining to pressure profile control and its influence on current drive and stability requirements.

Interaction between experiments and modeling is crucial to defining and reaching the final vision. The agenda (see Appendix II) was accordingly constructed with experimental and theoretical modeling talks interspersed. The focus was on identifying the underlying physics and most of the talks were detailed technical expositions. However, since it was necessary to obtain a significant level of consensus on the goal of AT research for further discussion of the path to make any sense, speakers were invited from several major laboratories to present overviews of their Advanced Tokamak programs and define their individual views of the ultimate goal.

As the preparations for the meeting progressed, however, it became apparent that not all the detailed technical points raised in the original charge could be addressed. The charge was accordingly refined to obtain a consensus on answers to the following three questions:

1. What is the ultimate vision of an Advanced Tokamak?
2. What are the present limitations that are impeding or preventing progress toward reaching this goal ?
3. What steps can be identified to remove the current obstacles, prioritized into immediate, medium term, and long term steps ?

The agenda (Appendix II) was developed to address this goal as follows: The first day was largely devoted to overviews aimed at defining the vision of what an Advanced Tokamak really means. Following this, several integrated modeling talks, plus comparisons between measured profiles and the target integrated modeling profiles were scheduled in order to provide some detail as to the present predictive capability of modeling efforts. This was followed by three sessions devoted to covering the three major components of any integrated scenario, namely: (i) transport, (ii) stability, and (iii) current drive. Discussion sessions, which were designed to provide a forum for reaching this goal, were organized as an integral part of the meeting. The discussion groups on the final day were explicitly charged with answering the above three questions.

III. Primary Conclusions

The workshop succeeded in providing a definite consensus on the answers to the three questions posed to the participants. For the first question, a consensus definition of an Advanced Tokamak was reached. For the second question, a number of obstacles were identified and these are elaborated below. However, one obstacle was virtually unanimously agreed to be the most pressing in terms of the ultimate viability of the Advanced Tokamak. Progress on this one issue would have important ramifications for the other issues as well. While it was recognized that means to address this issue are presently at a preliminary stage, some promising strategies for addressing it were nevertheless, identified.

The following is a summary of this consensus:

1. What is the ultimate vision of an Advanced Tokamak?

   A definite consensus emerged in the view of what the goal of an AT should be. An AT was generally defined as a class of tokamaks with simultaneously, but to varying degrees, the following three elements:

   (i) The reactor embodiment of such a device should operate in steady-state.

   (ii) An AT should be optimized for stability with respect to the profiles and cross section.

   (iii) The profiles should be optimized with respect to fusion performance, consistent with stability and steady state.

   However, while there was a consensus that we should be striving for simultaneous realization of these goals, there was no general agreement on the relative importance of the three elements and a minority of participants considered AT research as permitting emphasis on one or two aspects at the expense of the others; thus, the definition allows reduced emphasis on maintaining true steady state for example. Hence, no concise set of figures of merit could be agreed upon. In fact, it was generally agreed that a single set of figures of merit would be inappropriate since the AT concept should encompass the whole class of scenarios for which these elements are individually present to some degree, but with complete flexibility in the weighting of the different elements in order to maintain a healthy diversity in AT research. Nevertheless, it was unanimously agreed that:

   The crucial distinguishing feature of an Advanced Tokamak over a conventional tokamak is that these elements be accomplished through the use of active control of the current profile or shear profile and of the pressure profile or transport characteristics.

   It was generally recognized that the ARIES-RS embodies many of the features and challenges of this definition.

   Several implications are clear from the above definition of an AT:

   (i) For steady state, the pressure profile probably needs to be actively controlled in order to generate a bootstrap current that minimizes current drive requirements while maintaining satisfactory stability margins. Systems capable of driving current non-inductively will be required.

   (ii) Such a device probably will operate at high density for high fusion output.

   (iii) Wall stabilization is required in most AT scenarios in order to realize the maximum potential stability consistent with a large bootstrap current fraction.

(iv) Strong cross section shaping is a necessary condition for the simultaneous achievement of high β and good bootstrap current alignment, especially if wall stabilization is also invoked.

2. What are the present limitations that are impeding or preventing progress toward reaching this goal?

The development of the AT concept has undergone a great deal of progress over the past several years. Experiments have succeeded in improving peak performance through broadening the pressure profile via transitions to H–mode and also in extending the pulse length of moderate performance discharges to several energy confinement times. Simulations are becoming increasingly sophisticated as attempts are being made to couple equilibrium, stability, current drive, and phenomenological transport models to simulate steady state targets in a reasonable scenario, and a shift in the community's ideas of what is possible is now underway; namely that self-consistent modeling based on first principles may be tractable. Nevertheless, a number of obstacles presently limiting progress in Advanced Tokamak research were identified. These can conveniently be classified in the three areas comprising the major components of any integrated scenario, namely: (i) transport, (ii) stability, and (iii) current drive. However, it is recognized that these are interdependent and progress in one area can have important implications for the other issues; this is especially true of advances in transport modeling as discussed below.

(i) Transport:

The single issue that was unanimously agreed to be the most pressing in terms of the ultimate viability of the Advanced Tokamak is the following:

In both the experimental and modeling efforts, there presently exists an inadequate understanding of the transport barrier dynamics. This has two facets, one with respect to experimental efforts, and the other with respect to the self consistent modeling efforts:

a) In experiments, significant progress in advanced tokamak research would result if local pressure profile control, through manipulation of the local transport, can be realized. The requirement for this control capability comes from the need to relax and broaden local internal and edge pressure gradients in order to realize the predicted gains in the stability limits, while maintaining favorable bootstrap alignment with the total current profile.

It should be noted that this point applies to the whole class of advanced tokamak visions identified at the workshop. In general, pressure profile control would help mitigate current drive and stability challenges in regimes of high internal inductance (high ℓ_i), as well as reverse magnetic shear. In L–mode scenarios with internal transport barriers (ITBs), control of the ITB position and width is essential to avoiding otherwise inherently low ideal MHD stability limits. In H–mode scenarios with or without clear ITBs, control of the edge pressure gradients is essential to avoiding edge instabilities and thereby reaching the predicted ideal MHD stability limits. Another way to view this is that present experiments have not yet achieved bootstrap aligned profiles; the most direct way to control the bootstrap current is to control the pressure profile.

b) In modeling efforts, a complete time-dependent, self-consistent AT simulation requires a better understanding of transport barrier dynamics. Simplified dynamical models are now beginning to address the problem of predicting the bifurcation in transport barrier formation but these have not been fully developed or incorporated into integrated simulations.

   The tools required for developing a predictive modeling capability were discussed. Such tools would self-consistently address problems of current drive, current relaxation, transport dynamics, and stability. This modeling capability is a powerful asset in finding stable, robust, and achievable Advanced Tokamak solutions. A great deal of sophistication in self consistent modeling of Advanced Tokamak scenarios has been obtained in recent years, in which the full 2D equilibria are evolved with time dependent current drive simulations and transport models, and are coupled with stability calculations. However, the integrated modeling efforts are presently limited by the lack of realistic dynamical transport models for electron and ion particle transport, momentum transport, and electron heat transport. The integrated modeling calculations that include models for ion heat transport presently use static transport coefficients either computed from simple models or calculated from theory-based transport models, or phenomenological coefficients derived from similar experiments, but these coefficients are always fixed in time and are not yet coupled to other transport channels. They are presently unable to dynamically reproduce the bifurcation and hysteresis characteristics of transport barrier formation observed in the experiments. The relation between the local transport and the current profile is ambiguous in the experiments and therefore phenomenological models are not entirely satisfactory for extrapolating to new regimes. The dependence of transport barrier location, width, and power threshold on discharge shape, aspect ratio, and magnetic field are also not understood. Stability calculations are only now beginning to address the effects of barrier steepness and position on the β limits but are not yet systematically incorporated into integrated modeling calculations.

   In parallel with this progress, some of the critical elements of dynamical transport barrier models have recently been developed. A class of dynamical models exists that can reproduce various features of the transport barrier transitions and these models can now make qualitative predictions for transport barrier formation and hysteresis. If coupled as modules into an integrated simulation, they have the potential to address these questions quantitatively .

This issue was considered to be of a more fundamental nature than the other issues mentioned below; the rf current drive and stability issues are in a sense corrections to the present theory to account for more detail and are therefore essentially a continuation of current research to the next logical step. In contrast, development of an understanding and application of transport barrier dynamics as a tool for pressure profile control would introduce an entirely new degree of freedom into AT research that would accelerate progress in these other areas as well. Direct control of the location and intensity of transport barriers (internal or edge) would greatly aid in achieving improved stability, possibly up to the optimized ideal limits, and also allow improved bootstrap current alignment, thereby alleviating rf current drive requirements. In addition, the sensitivity of lower hybrid and electron cyclotron current drive schemes in the face of time- and space-evolving pressure gradients and rf-driven shear flows. has not yet been studied in detail.

(ii) Stability:

With regard to stability, it was recognized that ideal MHD predictions provide an accurate description of the upper limits to β that can be achieved. Nevertheless, the required bootstrap-aligned q and pressure profiles identified in numerical ideal MHD optimization calculations have not yet been obtained in Advanced Tokamak experiments utilizing transient means and many experiments are limited at significantly lower β values than the optimized targets. On the other hand, the optimization calculations do not routinely incorporate the pressure profiles with the steep transport barriers and corresponding bootstrap current profiles that are obtained experimentally. This is now beginning to be addressed in some studies but requires a more consistent effort.

Furthermore, the stability calculations do not presently include non-ideal modes, such as neoclassical tearing modes, and these are often observed to limit the achievable long pulse β values significantly below the ideal limits. It was recognized that, in contrast to the ideal stability, the resistive stability calculations are not yet at the same predictive stage as the ideal calculations but are instead “descriptive”, in the sense that they can reasonably well describe the stability of a given discharge after the fact.

(iii) Current Drive:

Regarding the issues for rf current drive, it was noted that there is presently a discrepancy between the predictions for off-axis ECCD and the observed current drive; the observed current densities are larger than predicted.

3. What steps can be identified to remove the current obstacles, prioritized into immediate, medium term, and long term steps.

Steps were identified that are aimed at eliminating or removing the obstacles within each area:

(i) Transport:

Possible steps that should be taken to remove the major transport obstacle were identified and discussed at length. It was generally agreed that confinement is adequate in present experiments and there is room to compromise and improve stability by reducing the steep local internal and edge pressure gradients; it was generally agreed that barriers that are too narrow result in steep pressure gradients that lower stability limits. Furthermore, barriers that are too internal, in addition to lowering stability limits, also minimize the overall fusion performance by reducing the volume of well confined plasma. It was recognized that the means to understand and control transport barriers, however, is presently at a preliminary stage. Nevertheless, some promising strategies were identified and a general consensus emerged that an understanding of the transport dynamics underlying pressure profile evolution, and it's ultimate control was not only necessary but is now possible.

With respect to the experimental and modeling sides of this issue, it was agreed that the following steps should be pursued:

a) In experiments, the development of means to create and control a “leaky” barrier would advance the development of Advanced Tokamak research considerably. Control would be required for both the location and intensity (i.e. a “dimmer switch”) of the barrier. The most promising strategies for achieving this appear to be through control of the E×B shear flow using rf or other means.

   A characteristic of transport barrier operation is their so-called bifurcation character; depending on certain not well understood conditions, a barrier either develops and confinement improves from that point on, or the discharge continues in it's initial confinement state with no noticeable steepening of the pressure profile. This applies to both ITBs and external barriers such as H–mode and VH–mode. The confinement improvement is strongly tied to a local steepening of the pressure gradient profile which appears to play a role as both a consequence of the improved confinement and as a driver for further confinement improvement — hence the observed bifurcation character. However, results from both experimental and theoretical research were discussed regarding the possibilities of moderating these gradients by the applications of external sources of E×B flow shear. Experimentally, some measure of transport barrier and pressure profile control, through controlling the shear flow, has been demonstrated in both TFTR and DIII–D. In TFTR, the balance between opposing sources of flow shear from the plasma pressure drive and the plasma’s externally driven toroidal rotational shear was modified to produce intermediate states between L–mode and ERS confinement. In DIII–D, a range of confinement states can be produced through control of various discharge parameters including L/H transition thresholds, and E×B shear flow control from co- and counter-beams. Experiments in DIII–D were reported that showed a weakening of the ion transport barrier in the presence of ECCD. It is not entirely clear whether this is due to a reduction in hot ion enhancement as T_e approaches T_i, or if it is a more direct effect of ECCD or ECH. Nevertheless, this should also be investigated as a possible ion transport control mechanism.

b) In modeling efforts, the capability for self-consistently modeling the pressure profile, current profile with current drive, and MHD stability, would be greatly enhanced by further increases in sophistication in the modeling of the transport barrier dynamics. These models should be explored further and incorporated into the integrated Advanced Tokamak simulations.

   Although the recent simplified dynamical models are not, as yet, predictive, they can reproduce the bifurcation in transport barrier formation and make testable qualitative predictions. For example, dynamical modeling indicates that intermediate confinement states like those observed in TFTR are accessible if opposing sources of flow shear, both external and internal, are present in the plasma. The framework of such a transport model and of others being developed, should serve as the basis of predictive, self-consistent models which could be used to scope out the range of barrier dynamics that might be realized under a particular set of conditions. In parallel with the theoretical work being done to identify promising dynamical models, the integrated modeling efforts should therefore begin to incorporate and test these models as plug-in modules. This will require an increasingly closely coupled interaction between the theory, the integrated modeling efforts, and the experiments, since the potential of such modeling can only be realized if it is to be tested against flexible tools and diagnostics.

New tools for flow shear generation need to be developed for both DIII–D and Alcator C–Mod in conjunction with the efforts at incorporating more self consistent dynamical models into the integrated simulations. In C–Mod, the proposed mode-conversion IBW should prove useful. The present understanding of rf-driven flow shear is far from being sufficient to predict power requirements for generating a particular sheared flow in a given location in the plasma.

(ii) Stability:

Experimentally, it is anticipated that ideal instabilities due to steep transport barriers can be avoided if the predicted optimized target profiles can be reached in experiments by improved profile control. Nevertheless, in the meantime, ideal stability calculations need to be continued to investigate the range of stability limits achievable for AT target equilibria with varying position and strength of transport barriers, both internal and at the edge.

The capability for predicting non-ideal stability limits can be improved by increased theoretical efforts in calculating Δ' for real geometry situations and benchmarking the predictions against high quality diagnostic measurements. This may require improved resolution in the current density profile measurements from MSE for example.

Experiments aimed at stabilizing neoclassical tearing modes (NTMs) through localized ECCD should lead to means to reliably overcome the present long pulse stability limits and reach the higher ideal limits.

(iii) Current Drive:

The discrepancy in predicted and observed off-axis ECCD should be resolved when sufficient ECCD power is available to make accurate measurements and predictions since the measurements in the current low power experiments are close to marginal. It was noted by several participants that this issue parallels a similar discrepancy some years earlier in lower hybrid current drive which was ultimately resolved by increased sophistication in the modeling of two-dimensional Fokker Planck physics as well as toroidal geometry effects in the LH wave propagation.

Steps should also be pursued to specifically address the efficiency of proposed current drive scenarios in the face of rapid changes in core transport barrier characteristics in both existing devices and in the family of possible long-range targets.

The proposed rf shear flow experiments in Alcator C–Mod using mode converted IBW should be pursued, and in parallel, the theoretical capability for modeling these flows needs to be developed. Further diagnostic capabilities for measuring the flows would be extremely beneficial for comparing with the models.

IV. Other Observations and Issues

Table I summarizes the remaining issues that were identified during the discussions and possible actions that could be taken to address them. In each case, there was general agreement that the issue should be addressed but no attempt was made at prioritizing them.

TABLE I

ISSUE	ACTION
MHD Stability	
• Low n ideal wall stabilization not sustained indefinitely	— Feedback coils. — Investigate rf induced rotation.
• Neoclassical tearing modes often limit long pulse high confinement	— Stabilization by ECH and/or ECCD. — Control of seed islands. — Develop better predictive resistive stability codes.
• Plasma edge stability	— Further diagnostic development for edge profiles and fluctuations
• Apparent dependence of β limit on B	— Need to express this dependence in terms of physically relevant parameters such as ρ^* and υ^*. — Dependence of ITB width on ρ^* appears likely to explain this.
RF/Noninductive Current Drive	
• Control of large bootstrap current profile	— Develop improved control of T, n profiles.
• Resolve disparity in experimental and calculated rf current drive efficiencies for ECCD	— Perform experiments at sufficient power to allow definitive test of theoretical versus measured efficiencies.
• Demonstration of sustained rf current drive profiles	— Perform experiments at sufficient power to sustain profiles.
• Can ECCD stabilize neoclassical tearing modes	— Perform experiments to demonstrate control.
• Develop other current drive options	— Develop mode conversion current drive.
• RF rotation drive is not yet understood	— No action identified.
• Need rf-induced shear flow tools	— Develop mode conversion current drive IBW.
• Pressure profile control	— Develop pressure control tools.

TABLE I (Continued)

ISSUE	ACTION
Transport/ITB	
• Control of ITB position and width	— Develop diagnostics for E_r, v_θ, and v_ϕ.
• Dependence of ITB on n, T is not well understood	— Develop diagnostics for E_r, v_θ, and v_ϕ.
• Effect of density limits on confinement is not well understood	— Use pellet injection to determine confinement versus n/n_{Green}.
• Limited understanding of AT options at reactor relevant densities	— Develop and study pellet fueling in order to reach reactor relevant densities.
• Electron transport not understood	— No action identified.
• Effect of T_e/T_i on ITBs is not understood	— Perform experiments with higher electron heating.
• Ion transport with rf is not well understood	— No action identified.
• Difference between rf driven flows versus momentum sources is not well understood	— Compare rf and NBI generated flows. — Improved diagnostics for flows.
• Develop first principles ITB and transport modeling capability	— Couple first principles models to integrated simulation codes.
• Hysteresis in barrier dynamics width, location, and power thresholds is not understood	— Explore dynamical first principles models.
• Density profile control is not complete	— Develop reactor relevant fueling options. — Develop improved control of impurity accumulation.
Theory, Modeling and Experimental Interactions	
• Dissemination of theory models requires improvement	— Develop new modules for the Fusion modules library. — Integrate with the National Transport Code Collaboratory Effort. — Implement improved access of codes to experimental data through MDS.
• Present experiments have not reached steady-state	— Develop better strategies for reaching relaxed V_{oh} conditions. — Extend pulse lengths.
• Experimental and target model profiles are not well matched	— Use ECCD/LHCD at sufficient power to generate bootstrap alighted profiles. — Improve modeling of transport to model experimentally achieved transport profiles.
• Communication: between experiment versus models and theory requires strengthening	— Participation by theorists and modelers in experimental planning and vice versa.

V. Recommended Actions for Research in the U.S. Program

1. C–Mod and DIII–D should aggressively continue to pursue the development of Advanced Tokamak target plasmas using RF current drive.

   While the tools to control the pressure are necessary for the future development of an AT, it was recognized that current drive tools are equally important. C–Mod and DIII–D have active or proposed programs for developing current profile tools and it is essential that these continue; the development of pressure profile tools should not be pursued at the expense of the programs for developing current profile tools. Both tools are needed.

   In the case of C–Mod, it was assumed that the proposed lower hybrid current drive system on C–Mod will move forward. This research can be pursued whether or not C–Mod plasmas can be made to generate reproducible core transport barriers, although the program would certainly benefit if the behavior of LHCD in the presence of barriers could be pursued. Pellet-induced core transport barriers (PEP modes) may serve as the basis for such research.

   In DIII–D, Advanced Tokamak research is intimately tied to ECCD. The high power ECCD upgrades for DIII–D should establish the theoretical basis of ECCD for future modeling. The research program is presently aimed at establishing the use of ECCD in plasmas with broad pressure profiles. A demonstration in which most of the plasma current is driven by ECCD would represent a significant step forward in advanced tokamak research. However, the possibilities for using ECCD in plasmas with a strong internal pressure gradient that might accompany an internal transport barrier should also continue to be explored.

2. Development of experimental pressure profile control capabilities, and especially rf-driven flow shear scenarios, should be pursued.

   At present, there is little emphasis in this area within the U.S. program. In the short term, both C–Mod and DIII–D should continue investigating pressure profile control possibilities indirectly by using control of the current profile (positioning of the minimum q surface). However, a tool that can directly control the transport barrier amplitude, width, and position is needed. In the medium term, mode-conversion IBW is planned for C–Mod and should be pursued. In the longer term, development of other tools that can directly control the transport barrier amplitude, width, and position should be supported. Possibilities include flow shear tools such as direct-launch IBW or shear Alfvén waves. The possibility of re-orienting a neutral beam source in DIII–D should be considered since it would allow the toroidal rotational shear to oppose or contribute to the pressure-driven flows in varying degrees and thereby increase the capabilities for testing of dynamical models.

3. Fully self consistent time-dependent modeling of current drive and stability in the presence of transport barriers should be pursued for the DIII–D and Alcator C–Mod tokamaks. Modeling of transport barrier dynamics, including rf and pressure-driven flow shear, should be improved and supported.

A significant outcome of this workshop was the recognition that many of the crucial elements necessary for understanding the transport barrier dynamics are at an early stage of development, but that the development of predictive tools for describing transport barrier dynamics can and should be pursued in the near and medium term.

A gap presently exists between the definition of advanced tokamak targets, and the experiences from present experiments. While gaps also lie in both rf and stability modeling, it was recognized that understanding of transport barrier dynamics and realistic modeling of it is a particularly conspicuous need. The modeling presently uses transport coefficients from simple or theory-based transport models, or derived from similar experiments that are not dynamically evolved. While they can simulate a static barrier, these models cannot reproduce the dynamics of barrier formation and evolution.

In the near-term, self consistent modeling, which includes stability, current drive, and transport, can be continued using a range of reasonable heuristic rules for transport barrier onset and evolution and phenomenological or theory-based transport coefficients. An example of such assumptions in the self-consistent modeling might include linking the boundary of the region of improved transport to the time-varying location of the minimum of the q profile; presently, this is only done in a static sense with the transport coefficients set to correspond to the steady state profiles. Modeling of the rf-driven shear flow also needs to be included self consistently in these simulations. This needs to include modeling of the wave physics to understand deposition, the width of the shear layer, the efficiency expected for driving such flows, and the structure of the expected perturbed electric field. It also includes modeling of coupling between the rf antenna and the plasma. Understanding the difficulties of coupling of IBW on DIII–D and TFTR may help identify a pathway forward.

4. Increased interaction between theory, modeling, and experimental efforts should be pursued.

Modeling has two distinct roles. The generally undisputed view of modeling efforts is that they can provide a detailed post-analysis diagnosis of a given experiment. However, it is not universally conceded that modeling can also realistically provide a goal and direction for AT research. This is changing and it is now becoming more widely acknowledged that modeling can and should be useful in leading the experimental efforts if the goals identified from modeling are flexible and respond to new experimental results and to new theoretical ideas.

At this workshop it was recognized that further progress could be accelerated by more closely coupling the experimental, modeling, and theoretical efforts; specific experiments should be performed that are designed to explicitly test models, and conversely specific modeling designed to simulate individual experiments should be performed and directly benchmarked against experimental data. Theorists and modelers should be more involved in the planning of experiments, including proposing experimental tests of their own predictive models. Transport modelers should attempt to reproduce important generic features in the data, such as barrier expansion, spontaneous generation of sheared flows, and threshold conditions, for example. This process then needs to be continually iterated as the experiments and modeling mature. As an adjunct to this, improved diagnostics are required that can test theory and modeling predictions, and modeling and theoretical predictions that are measurable are clearly needed.

Appendix I
Workshop Charge to Invited Speakers

PHYSICS REQUIREMENTS FOR ADVANCED TOKAMAKS
Experimental Status, Modeling, and Future Directions
March 9-11 1999, General Atomics

A workshop on the present status and future goals of experimental and modeling efforts for Advanced Tokamak (AT) plasmas will be held on March 9–11, 1999, at General Atomics. It is aimed at identifying the steps required in the U.S. in experiments and modeling to help ensure success in developing the advanced tokamak reactor concept. The status and plans of near-term current drive experiments and self-consistent modeling efforts will be discussed, with emphasis on identifying needs and gaps that must be filled to best define a long-term vision of the AT. Since current profile, transport, and stability are intimately connected in any AT concept, the role of pressure profile control in enabling a self-consistent vision of the AT will also be a focus.

As output for the workshop, a summary will be produced that outlines the near-term research road map, the characteristics of the long-term goal, and the proposed path required to achieve that goal. This document will be used as input into the Snowmass meeting this summer. Needs in the near-term (1–3 year), midterm (3–5 year), and longer (5–10 year) time frames will be described. These might include needed current drive power improvements, pulse length extensions, needed advances in self-consistent plasma modeling, and required efforts in pressure profile control.

To help focus the discussion, it is proposed that the participants present work on a few topics. Discussion on some points will require some work between now and the meeting. These will include modeling surrounding existing and planned experimental efforts, as well as modeling work that might elucidate profile control issues for a reactor-scale AT. The specific schedule and slate of speakers for the meeting will be announced in mid February. The proposed topics of discussion are as follows:

1. Description of a reactor-grade AT plasma

    - The current profile and current drive requirements
    - The pressure profile
        – Alignment of bootstrap current with total current
        – Stability properties with desired current and pressure profiles
    - Needed current drive efficiencies
    - Required confinement properties
        – Transport/transport barrier characteristics consistent with high beta
        – Description of and gaps in experimental database that supports this regime

2. Connection to the long-range goal: near-term experiments and modeling

    - Description of present and near-term experiments (0–3 years)
        – Driven, bootstrap, and inductive current profiles with planned experiments

  - Expected current drive efficiencies
- Self-consistent modeling of CD, transport, and stability
  - Improvements needed to enable definition of a credible steady state AT target
  - Physics gaps that need to be filled for transport and stability calculations
- CD physics in near-term and long-range AT targets
  - Changes in CD efficiencies between present experiment and long-range targets
  - Changes in localization properties
  - Robustness of CD scheme to transport barrier dynamics (e.g. expansion, collapse)

3. Pressure profile control and its influence on CD requirements and stability

   - The possibility of relaxing CD demands with transport barrier control
   - Research on pressure profile control techniques
   - Transport barrier dynamics: reasonable assumptions for self-consistent modeling

PHYSICS REQUIREMENTS FOR ADVANCED TOKAMAKS

Experimental Status, Modeling, and Future Directions

March 9-11 1999, General Atomics

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A Registration Fee of $30 per participant, payable on arrival, will be charged to cover coffee break service and incidental expenses. It is planned to place all viewgraphs on the WWW. Speakers are therefore urged to make electronic versions of their talk available prior to the meeting.

Please indicate if you are not a U.S. Citizen since some additional paperwork is then necessary.

A block of rooms has been reserved under "General Atomics" at the Residence Inn, 8901 Gilman Drive, La Jolla, CA 92037, Tel: 1-800-331-3131 or 619-587-1770, Fax: 619-552-0387, at a rate of $119 plus tax, single or double occupancy, including breakfast. The block will be held until February 16, after which date the rate may not be available.

If you have any questions or require directions in San Diego, please contact Alan Turnbull at 619-455-4042 (turnbull@gav.gat.com) or Beulah Koz at 619-455-2837, Fax: 619-455-2838, (koz@gav.gat.com).

Appendix II
Agenda

PHYSICS REQUIREMENTS FOR ADVANCED TOKAMAKS
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Note: 1-hour talks include 20 min. discussion
45-min. talks include 15 min. discussion
30-min. talks include 10 min. discussion

Tuesday, March 9 (Room 15-019)

7:30	Continental breakfast provided	
8.15	Welcome	T. Simonen
8:20	Preliminary remarks	A. Turnbull

Overviews (Session Leaders: a.m. E. Synakowski; p.m. A. Turnbull)

8:30	Overview of C–Mod AT Program	M. Porkolab
9:30	TFTR Perspectives on Advanced Tokamak Research	M. Zarnstorff
10:30	**Break**	
10:45	Overview of DIII–D AT Program	T. Taylor
11:45	**Lunch**	
12:45	Steady State Operation for an Advanced Tokamak: Results and Perspectives from JET and Tore Supra	A. Becoulet/ X. Litaudon
1:45	JT–60 Plans for the Advanced Tokamak	T. Ozeki
2:45	Perspectives on AT Issues from Considering JET and TFTR Operations	M. Bell
3:45	**Break**	

Long Range AT Scenarios and Requirements (Session Leader: P. Bonoli)

4:00	Reactor Options for Advanced Tokamaks	S. Jardin
4:30	ARIES-RS Advanced Tokamak Analysis and Issues	C. Kessel
5:00	**Discussion:** What do long range scenarios assume that have to be addressed in the near term? (**Leader: T. Taylor)**	
6:00	**Reception — GA Cafeteria**	

Wednesday, March 10 (Room 07-217)

Present and Targeted AT Plasma Characteristics (Session Leader: X. Litaudon)

8:00	ITB Formation Experiments in C–Mod: PEP Mode During Current Ramp-up and ITB Induced L/H Transitions	M. Porkolab
8:30	Lower Hybrid Current Profile Control Studies in Alcator C–Mod	P. Bonoli
9:15	Self-Consistent AT Scenario Modeling for DIII–D	M. Murakami
10:00	Comparison of Measured DIII–D High Performance Discharges with Steady State Target Profiles	B. Rice
10:30	**Break**	
10:45	**Discussion:** What needs to be done to improve matching between simulations and experiments? **(Leader: R. Hawryluk)**	

Current Drive Physics and Systems (Session Leader: A. Becoulet)

11:45	Off-axis ECCD on DIII–D: Results and Issues	C. Petty
12:15	Tokamak Current Profile Control Issues	C. Kessel
12:45	**Lunch**	
1:45	Current Drive Trade-Offs for Reactors: Considerations for Central, Off-axis and Edge Current Drive	T.K. Mau
2:15	Fokker-Planck Modeling of Advanced Tokamak Scenarios	R. Harvey
2:45	**Discussion:** Near- and Long-Term Research Needs for Auxiliary Current Drive (**Leader: T. Luce)**	
3:30	**Break**	

MHD Stability of Advanced Tokamak Modes (Session Leader: T. Ozeki)

3:45	Ideal MHD Stability Studies and Issues for AT Operation in Alcator C–Mod	J. Ramos
4:15	Stability Modeling of DIII–D Advanced Tokamak Scenarios	L. Lao
4:45	**Discussion:** What issues remain for MHD stability? (**Leader: M. Porkolab)**	
5:30	Adjourn	

Thursday, March 11 (Room 07-217)

Pressure Profile Control: Internal Transport Barrier Physics

(Session Leader: F. Romanelli)

8:30	Transport Barrier Formation and E×B Flow Shear	C. Rettig
9:00	Electron Transport in DIII–D NCS Discharges	C. Greenfield
9:30	Turbulence and Microinstability Considerations for Advanced Tokamak Operation	W. Dorland
10:00	RF Generated Shear Flows for Control of the Pressure Profile	J.R. Wilson
10:30	**Break**	
10:45	RF-Driven Shear Flow Effects on Ion Temperature Profiles in Alcator C–Mod	D. Ernst
11:15	Dynamic Modeling of Transport Barrier Formation and Evolution	D. Newman
12:00	TFTR Transport Barrier Dynamics and Comparison to Dynamical Models	E. Synakowski
12:30	**Set up break-out groups**	
12:45	**Lunch**	
1:45	**Discussion:** What are the near- and long-term needs in current drive, stability, and pressure profile control research? (Breakout — Rooms 07-215, 07-120 and 13-107)	
3:15	Return to 07-217 — **Break**	
3:30	**Summary Session**	
4:30	Adjourn	

Appendix III
Participation List

ADVANCED TOKAMAK WORKSHOP
March 9-11 1999, General Atomics
Attendees

Batchelor, Don	ORNL
Becoulet, Alain	CEA-Cadarache
Bell, Mike	PPPL
Bernabei, Stefano	PPPL
Bonoli, Paul	MIT
Chu, Ming	GA
De Marco, Francesco	ENEA, Frascati
Dorland, William	U. Maryland
Ferron, John	GA
Foster, Mark	DOE
Gohil, Punit	GA
Greenfield, Charles	GA
Gryaznevich, Mikhail	Culham
Harvey, Robert	CompX
Hawryluk, Richard	PPPL
Houlberg, Wayne	ORNL
Jardin, Steve	PPPL
Johnson, Larry	PPPL
Kessel, Charles	PPPL
Kim, Jinchoon	KBSI
Kim, Jin-Yong	KBSI
Lao, Lang	GA
Lin-Liu, Yuh-Ren	GA
Litaudon, Xavier	CEA-Cadarache
Luce, Tim	GA
Mau, T.K.	UCSD
Meade, Dale	PPPL
Murakami, Masanori	ORNL
Nevins, Bill	LLNL
Newman, David	U. Alaska
Oktay, Erol	DOE
Ozeki, Takahisa	JAERI
Peng, Martin	PPPL
Petty, Craig	GA
Politzer, Peter	GA
Porkolab, Miklos	MIT
Ramos, Jesus	MIT
Rettig, Curt	UCLA
Rice, Brad	LLNL
Romanelli, Francesco	ENEA, Frascati
Rutherford, Paul	PPPL
Sauthoff, Ned	PPPL
Simonen, Tom	GA
Stallard, Barry	LLNL
Synakowski, Ed	PPPL
Taylor, Tony	GA
Turnbull, Alan	GA
Uckan, Nermin	ORNL
Wesley, John	GA
Wilson, Randy	PPPL
Zarnstorff, Mike	PPPL