

THEORY OPPORTUNITIES FOR ADVANCED TOKAMAKS

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The advanced tokamak (AT) program is aimed at improvement of the tokamak concept towards higher performance and steady-state operation through internal profile modification and control, plasma shape optimization, and MHD and microturbulence stabilization. The dependence of the core performance on the boundary conditions, and the operational regimes envisioned, put more stringent requirements on the divertor and edge plasma. Thus, AT research necessarily encompasses the following four topical areas:

- i) Steady-state or long pulse scenarios with an optimized bootstrap current fraction and self-consistent, non-inductive current drive;
- ii) Extended MHD stability of long pulse/steady-state operation;
- iii) Improvements in core transport modeling in the presence of internal transport barriers and extension of the physics to make contact with the pedestal and edge modeling; and
- iv) Extensions of edge and pedestal transport modeling towards the lower collisionality core with the ultimate goal of being able to consistently model from the scrape-off-layer (SOL), across the separatrix and pedestal, and into the deep core.

All four of these areas involve substantial theoretical challenges and could lead to new insights that would play a crucial role in improving overall performance. The division into four topical areas is somewhat artificial since in an AT all four can be strongly coupled, and integration of the physics is required to predict the performance of an operating scenario. Hence, the development of integrated modeling capability needs to be an important component of the AT theory program.

Steady State Profile Control

Steady state operation studies in advanced tokamaks are aimed at optimizing the bootstrap current and providing the remaining current by non-inductively driven current, and employing wave heating to control temperature profiles. AT scenarios performed to date have focused on achieving steady state operation while preserving ideal-MHD stability without and with conducting walls. Without a wall the primary parameter maximized is the bootstrap current fraction, subject to the no-wall stability constraint. These studies arrive at an optimized geometry characterized by an aspect ratio of 3, an elongation of 1.8 and a triangularity greater than 0.5. Stable configurations without conducting walls having a 75% bootstrap current fraction have been predicted for a relatively broad pressure profile (p_{\max}/p_{ave} about 3) and a reversed magnetic shear profile having a q_{\min} greater than 2 at

$r(q_{\min})/a$ approximately equal to 0.8. The remaining current, which must be externally driven, as well as its detailed profile shape is consistent with lower-hybrid current drive analyses both in Alcator C-Mod and in ITER-FEAT scenarios. Indeed, recent experiments in JT-60U have achieved current profiles and bootstrap fractions almost identical to the theoretically optimized ones. With a conducting wall much higher bootstrap fractions are found (90% or greater), but these studies are sensitive to the pressure profile which is not specified in a fully self-consistent manner. Moreover, achieving high bootstrap fraction in a high-Q burning plasma will require the development of novel means to control the plasma density and/or pressure profiles.

One important outstanding issue is the possibility of increasing the beta and the bootstrap fraction by exceeding the no-wall stability limit with a self-consistent non-inductively driven current in the presence of a passive wall plus active feedback and/or plasma rotation. Without the effect of the conducting wall, the optimized bootstrap fraction is limited to about 75% at a Troyon-normalized beta of about 3 by the onset of the ideal MHD $n = 1$ external current and pressure driven kink ballooning instability. With wall stabilization, active feedback control, and/or rotation the external current drive requirement should be reduced and the plasma beta, and therefore the fusion yield, increased. Of course, higher n peeling and ballooning, as well as $n = 1$, stability would have to be maintained. With the reduced external current drive requirement, electron cyclotron current drive, attractive because of its localizability and its compact technology, is also a candidate for off-axis current profile control.

Another outstanding issue is the consistency of the AT optimized profiles with plasma transport processes either in an externally heated or in a fusion burning situation. Most preliminary analyses performed to date have used models of the density and temperature profiles that have specified shapes that correspond to experimentally observed edge (H-mode) and/or internal transport barriers, but which have not been verified as being self-consistent with time-dependent transport evolution, since the core and edge anomalous transport processes are not well enough understood on the long time scales of interest. These specified profiles have been shown not to degrade the AT performance provided the optimized current profile can be maintained and this has been shown to be the case by computing its lower-hybrid and bootstrap current components consistent with the assumed density and temperature profiles. It should be noted that the lower-hybrid consistent optimized current profile has a low edge current density, even for simulations with H-mode types of pressure pedestals. This low edge current density result is a desirable behavior for the current density component of the MHD instability drive responsible for kink and peeling modes. Lower, less favorable stability limits and bootstrap fractions would be

obtained if high edge current pedestals were to develop. Understanding how edge oscillations such as edge localized modes (ELMs) control the edge pedestal, and identifying operating regimes where these modes do not lead to significant energy loss is of high priority. Localized variations of the MHD equilibrium in response to RF heating and current drive can significantly affect stability. Hence, a complete assessment of these effects requires self-consistent solution of transport, MHD equilibrium and heating/current drive, combined with stability analysis.

Extended MHD Stability

The understanding of the physics of β and current limits are fundamental to optimization of tokamak operation since plasma confinement is roughly proportional to plasma current and fusion power density is proportional to β^2 . The constraints imposed upon β and current by static ideal MHD stability provide basic limits which generally cannot be exceeded. Both high- n local modes and low- n global modes impose limits. Boundary conditions, in particular the presence of a conducting wall, can modify the limits as can additional effects including resistivity, viscosity, rotation, fast ions and nonlinear effects.

The ideal MHD stability thresholds are sensitive functions of the pressure and current profiles, cross-section shapes, and in the case of the external kink, the wall conditions. Sophisticated numerical codes are available to compute ideal stability MHD β limits, and new AT experiments are designed using shape and profile optimization to target an upper β limit as a function of the location of a perfectly conducting wall. Non-ideal MHD effects often stand in the way of achieving this upper limit. The instabilities driven by non-ideal effects have slower growth rates than ideal instabilities, hence, are of particular concern for long pulse/steady-state AT operations where they usually become observable. Fortunately, because of the slower growth rates, they are often amenable to mitigation through feedback control. Understanding non-ideal (or extended) MHD instabilities and devising means to stabilize them offer very high pay-off for AT operation.

AT operating regimes such as the reverse magnetic shear configuration benefit considerably from wall stabilization. Wall stabilization using resistive walls requires plasma rotation or some form of feedback to maintain stability for times longer than the characteristic resistive decay time of the wall. Code results taking into account resistive walls indicate that toroidal plasma flow, in conjunction with dissipation in the plasma, can open a window of stability with stable plasma β values exceeding twice those predicted by Troyon scaling law with no wall. Because of the demand on plasma rotation, a reliable

dissipation model to predict the critical rotation is crucial. Present theoretical predictions depend sensitively on the dissipation models used at the mode resonant layer and upon the number of resonant rational surfaces in the plasma. Validation of these models against experiments has only been partially successful. Moreover, recent experiments suggest that the explanation for the observed gradual loss of the plasma rotation, essential for stability of the resistive wall mode (RWM), lies in the interaction between the marginally stable RWM, the plasma rotation, and intrinsic or induced error fields.

Analytic theory, which is essentially independent of plasma models, has shown that marginally stable resistive wall modes can strongly damp toroidal plasma rotation, and that simple error field correction coils can prevent this damping. Work remains on the inclusion of toroidal rotation effects in the codes that are used to design and interpret wall mode experiments. For future large devices, it may not be practical to establish sufficiently strong plasma rotation relative to the resistive wall for complete stabilization. Therefore, other means are being studied which make the resistive wall appear ideally conducting to the plasma. Theoretical efforts have been focussing on designing feedback schemes for a single mode. Significant work remains to explore feedback stabilization of multiple modes and combinations of rotation and feedback stabilization, which may be necessary for optimum control.

Classical and neoclassical tearing modes (NTMs) have been observed in experiments and like RWMs are a particular concern for long-pulse AT discharges. They have been observed to cause β collapses and even termination of discharges by disruption. Because classical tearing modes often saturate nonlinearly in small magnetic islands, they were thought to be relatively benign. However, theoretical developments in recent years have led to an understanding of neoclassical effects (i.e., the role of the bootstrap current) which in the presence of externally-induced or nonlinearly saturated "seed" islands, can drive tearing instabilities that are much more deleterious. Controlling NTMs require understanding the instability onset. While the presently available cylindrical modified Rutherford equation can provide a number of qualitative features observed in experiments, it cannot quantitatively predict the onset of the NTM instability. Additional important physics including transport and polarization drift effects inside the island have not yet been resolved satisfactorily. Toroidal and even three-dimensional effects can be important. The study of the interaction of multiple NTMs when rational surfaces are close to each other, as well as the interaction between resonant and non-resonant modes have only begun. The success of AT regimes will likely be determined by whether NTMs can be avoided or mitigated, and theoretical understanding of NTMs is an integral part of such determination.

Tokamak performance depends strongly on the stability and dynamics of the plasma edge. The edge region, which provides a transition from the hot plasma core through the separatrix to the material surfaces of the divertor and first wall, impacts core confinement and overall β limits as well as plasma-wall interactions and divertor design. In H-mode plasmas, an edge transport barrier causes a sharp pedestal-like structure to develop in the edge temperature and density profiles. The height of this pedestal largely determines the confinement properties of the entire plasma, according to both empirical observations and many transport theories. However, theoretical analysis of edge localized modes (ELMs) which may control the pedestal height is complex, in part because the sharp pressure gradients and consequent large bootstrap currents in the H-mode edge can destabilize kink, peeling and ballooning modes over a wide range of toroidal mode numbers (n). No single MHD code can compute the stability over the entire range of n . The intermediate n -modes, which are most likely responsible for ELMs, turn out to be most challenging to compute. A number of other factors, including kinetic modification due to finite gyroradius effects, x-point geometry and plasma flow must be retained, and nonlinear simulations needed to understand the detailed evolution of ELMs and profiles in the edge region are only beginning. The understanding of edge pedestal dynamics will go a long way in ascertaining the performance of AT plasmas.

Core Transport Modeling

By taking the pedestal temperature and density as boundary conditions, a number of reduced transport models (models that provide transport coefficients) have demonstrated successes at predicting the transport in L-mode and H-mode plasmas, with and without internal barriers. These models tend to be stiff, and the stiffness leads to predicted fusion power performance in reactors which has a stronger than linear dependence on the projected edge pedestal temperatures. Hence there are two key (partly overlapping) categories of issues for transport theory: those related to the development of true theory-based core transport models (and their solution), and those related to the prediction of pedestal temperatures. We address the former here, and the latter in the next section.

Over the past few years, great progress has been made, both in experiment and in direct numerical simulation, in obtaining quantitative results for the turbulent ion heat flux associated with ion temperature gradient (ITG) modes. What remains is to use our improved understanding to determine if it is possible to obtain a quantitative theory based expression for the diffusivity. The most successful present-day transport models are semi-theoretical, in that there are adjustable parameters that are set by fitting databases of experimental results and/or simulations. The development of a true, validated, theory-

based transport model has been an outstanding challenge for a generation and remains so today, although there have been many improvements. A number of critical issues remain.

One issue, particularly important within transport barriers, is electron temperature gradient (ETG) mode physics, and its impact on momentum and particle transport. Experiments show that the ion toroidal momentum and particle transport remain above neoclassical levels within a transport barrier. None of the existing low-k drift wave based transport models can explain this anomaly, since both the ExB and alpha stabilization (magnetic shear stabilization introduced by the Shafranov shift) mechanisms in these models bifurcate to completely shut down the low-k turbulence leaving the ion channel neoclassical. The observed electron transport also is far above neoclassical, qualitatively consistent with electron heat transport predicted for high-k ETG modes. Gyrokinetic stability calculations of the critical electron temperature gradient for ETG modes have also found that the electron temperature profile follows closely this threshold within an internal barrier. The present ETG mode model is incomplete in several respects. The ion physics needs improvement. It is known from gyrokinetic quasi-linear calculations that the ETG modes do produce some ion as well as electron transport which may be expected to survive ExB shear stabilization. Furthermore, recent nonlinear simulations of ETG modes have also identified higher levels of transport than expected from the simple isomorphic ITG/ETG model (identical transport models with ion and electron parameters interchanged). This may be due to differences in the saturation mechanism which forces the zonal flows to be much smaller and allows streamers to produce large transport levels.

A second issue, important for both internal and external barriers, is the need for treating shaped magnetic geometry to accurately find the thresholds for electromagnetic ballooning modes, and accurately model the Shafranov shift which can be a stronger stabilization effect than ExB shear in some cases. This shift is particularly important for a tokamak reactor, as the ExB shear does not scale favorably to reactors which necessarily have much lower dimensionless gyroradius ρ^* . Present models using either simple infinite aspect ratio shifted circle geometry or electrostatic approximation are not accurate enough. For example, they neglect the enhancement of the ITG growth rates due to drift-Alfven coupling in the outer part the plasma which could play an important role in limiting the expansion of internal transport barriers into the positive magnetic shear region in AT reverse shear operation. The issue of getting the Shafranov shift and the electromagnetic ballooning mode threshold, as well as the shear of the radial electric field, correct may also be crucial in modeling the H-mode edge barrier region.

A third issue is the role of intermittency and large-scale events in transport. There is evidence from both experiments and simulations that transport may be modified by

bursts which propagate through the plasma. The challenge is to elevate sandpile models of avalanche phenomena to full-physics models with quantitative predictive values.

Finally, there are a number of computational challenges even though advanced simulation tools based on near-first-principles gyrokinetic equations have had increasing success in reproducing features observed in experiments. Continued development of these codes to include full electromagnetic effects, collisions, multiple species, impurities, and extension of the simulation domain is an ongoing need. Another significant challenge is the development of efficient techniques to solve theory-based moment descriptions with stiff, highly nonlinear transport coefficients.

EDGE AND PEDESTAL MODELING

As noted in the preceding sections, the edge pedestal provides an essential boundary condition for core transport models; hence its description is critical and a well-validated model for predicting edge pedestal temperature is needed. In addition, the edge behavior determines particle fueling to the core and power flux to material boundaries. The phenomena that are experimentally observed and in need of improved understanding include:

- (i) The low (L mode) to high (H mode) confinement transition associated with the generation of a reduced transport region referred to as an edge transport barrier in the pedestal region (possibly due to strong radial variation in the radial electric field in the vicinity of a separatrix),
- (ii) The Greenwald density limit which prevents the core density from being raised further in H mode and results in the edge losing its transport barrier and reverting back to L mode,
- (iii) The various types of edge localized modes (ELMs) observed in all tokamaks and other edge fluctuations thought to only influence particle loss (the quasi-coherent mode, QCM in Alcator C-Mod and edge harmonic oscillations in DIII-D), as well as field aligned structures observed in the SOL, and
- (iv) The mechanism that sets the temperature at the top of the pedestal, which controls the level of core transport.

The edge pedestal may well involve interplay between MHD and barrier formation. It will require a dynamic treatment of the ELMs, which are thought to be a cyclic MHD stability breakdown of the barrier, which then reforms. Present transport models include the critical pressure limit imposed by high- n ballooning modes, but do not include intermediate- n peeling and ballooning modes. A working model will need coupling between the short wavelength transport physics and the longer wavelength MHD physics.

It is also important that bootstrap current, which is formed and destroyed in the pedestal, be included.

Turbulence modeling at the edge of tokamaks requires dealing with added physical complications such as:

- (i) Strong density and temperature variation in the pedestal and edge transport barrier region resulting in short radial scale lengths and a transition from the long mean free paths of the core to the shorter mean free paths of the SOL,
- (ii) The geometrical change from closed magnetic surfaces to open field lines at the separatrix that impinge on divertor plates or limiters, and the presence of open magnetic field lines intersecting the divertor plates, and
- (iii) The atomic physics associated with ionization, impurity radiation, and charge exchange coupling to the neutrals.

Recent theory and simulations indicate that magnetic shear in the vicinity of the x-point further destabilizes ballooning modes by enhancing the resistivity to remove line bending stabilization. These modes extend appreciably into the closed-flux-surface plasma (into the pedestal region), and a remnant seems to survive even in the presence of H-mode-like levels of velocity shear. Other work has suggested that resistive ballooning modes may be unstable even without x-point effects; and in a limited plasma, sheath impedance can play a destabilizing role similar to x-point shear. Hence, these modes are strong candidates for edge turbulence in L and H mode and for understanding of edge pedestal formation. However, much work remains to be done in terms of the development of scalings and analytic transport coefficients, and inclusion of information from turbulence models in long-time evolution transport codes.

There has been much interest lately in observations in a number of tokamaks which suggest that edge transport is sometimes dominated by large-amplitude, field-aligned radially propagating, localized structures (“blobs”). These have been interpreted theoretically as large-amplitude interchange instabilities. There are many questions about these objects which remain to be answered including how they are formed, what physics is required to properly describe them, and what their impact is on transport.

The preceding issues, like essentially all boundary-plasma modeling, have been addressed via fluid models, which are based on short mean free path collisional transport along B , with flux limiting to account at some level for finite mean free paths. As a result, it is not clear how the behavior of the numerically observed modes in the pedestal region will be modified by improved treatments of long mean free path effects. To extend these models further into the core requires consideration of a regime in which the mean free path is comparable to or longer than the connection length. Therefore, a fluid model must be

formulated which is valid for long as well as short mean free paths. The development of such a model is a difficult challenge for plasma theory and will require a substantial analytic effort prior to numerical implementation. Indeed, the development of an appropriate fluid model may be more difficult than its implementation since the techniques for numerically solving coupled fluid equations in three dimensions already exist. Such an effort is warranted, and indeed probably necessary to further improve AT performance if we are to understand the coupling of the edge and core, and properly evaluate the radial electric field everywhere. The core turbulence simulation community had developed gyrofluid models in an effort to incorporate kinetic effects in fluid equations. These equations have been shown to have some deficiencies. As a result, the community has largely gone over to gyrokinetic models, but development of improved fluid equations for the core would clearly be valuable.

In addition, the existing edge turbulence codes do not retain the effects of neutrals. The neutrals may play a role in setting the pedestal width because of their small penetration depth and determining the radial electric field just inside the separatrix because of their very large diffusivity. The poloidal variation of the neutral density may also impact the ion flow and drive convective fluxes.

Finally, just as the core turbulence community has largely made the transition from (gyro)fluid to gyrokinetic codes, an effort to develop fully kinetic edge codes would be valuable. There are two approaches to doing so; one is to add edge effects (neutrals, steep gradients, closed-open geometry, x-points) to core gyrokinetic codes; the other is to develop a kinetic version of a full-geometry short mean free path edge code. There is at least one such effort beginning in Europe.