Research Needs Workshop (ReNeW)

Burn Control and Thermal Stability

S. M. Wolfe
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Issue: Burn Control and Thermal (In)stability

Control of the operating point in a self-heated plasma is required for ITER Q>5 scenarios as well as for DEMO and reactors. In a burning plasma with dominant self-heating (alpha heating), feedback control of the fusion power output is required. In the case of DEMO or a reactor this control is a fundamental requirement, namely the regulation of the output of the power plant. For ITER the issue is control of the chosen operating point. In either case, excursions in the alpha power correspond to potentially unacceptable variation in the heat load (power exhaust) on plasma facing components which are close to operational limits, as well as leading to modification of the MHD stability properties of the plasma potentially leading to disruption.

Background

The operating point of a burning plasma may be unstable to temperature (or pressure) excursions, depending on details of the sensitivity to the variation of the plasma loss power relative to that of the alpha heating power. Power balance is expressed as

$$dW/dt = P_\alpha + P_{heat} - W/\tau_E - P_{rad}$$

where P_{heat} includes ohmic, auxiliary bulk heating and current drive power. The alpha heating $P_\alpha \sim n_D n_T \langle\sigma v\rangle$ scales approximately proportional to T^x with $2.5>x>1.5$ in the range of interest $8<T<25$keV . The stability of the operating point is determined by the scaling of the loss power, with gyroBohm scaling corresponding to $\tau \propto T^{-2.5}$ and Bohm scaling to $\tau \propto T^{-2}$. Referring to the commonly used empirical confinement scalings, IPB98y2 scaling ($\tau^{98y2}=0.144 H I^{.93} B^{.15} n^{.41} R^{1.97} \varepsilon^{.58} \kappa^{.78} M^{.29} P^{-.69}$) results in

$$W/\tau^{98y2} = -P_{tr} \propto n^{1.9}\, T^{3.2}\, (H\, I)^{-3.2}$$

with rather good prospects for thermal stability as the conductive loss power increases more rapidly with temperature than the fusion power, while the more Bohm-like ITER-89P scaling ($\tau^{89} \propto H\, I\, n^{.1}\, P^{-.5}$) gives

$$W/\tau^{89} \quad = -P_{tr} \propto n^{.8}\, T^{2}\, (H\, I)^{-2}$$

with rather marginal stability against temperature excursions. The burn stability may be more readily visualized on a POPCON plot[1], which depicts equilibrium contours of heating power in the (n,T) plane, including radiation loss, depletion by thermalized alphas, etc. An operating point to the right of the separatrix (high temperature, low density), where the required net power increases with temperature, is stable against thermal excursions, while one to the left side of the graph (lower temperature, higher density) will be unstable.

Thermal stability is typically not a governing consideration in the design of an operating scenario, and DEMO / reactor designs have been proposed with both stable and unstable burn points. The ARIES-AT point design[2] features a nominally stable operating point at the relatively high temperature of 18.5 keV, chosen because of improved current drive efficiency. The helical reactor design FFHR[3] proposes to operate at an unstable burn point (n_{20}~6, T~8.5) to take advantage of favorable density scaling observed in stellarators.

A variety of actuators have been proposed for stabilization of thermally unstable burn points and for regulation and control of stable burn points, incorporating a range of control strategies.[4,5,6,7,8] Possible actuators include auxiliary power (for driven systems), fueling, and impurity injection. Actuators for particle control include gas puffing and cryogenic pellet injectors. More discussion of specific instances appears below.

Measurements for the various quantities of interest are potentially available. The fusion power (proportional to P_α) itself is observable with essentially zero lag by monitoring the flux of 14.5 MeV neutrons. This is an important consideration, since the plasma response to variations in reactivity experiences a lag associated with the alpha slowing down time and the energy confinement time, typically amounting to a delay of several seconds. Since actuators with response times of the same order are available, we expect that in principle the system is both observable and controllable.

Neutron monitors are in common use and can be expected to be used on ITER and DEMO. Profiles of neutron emissivity are planned on ITER, but would only be employed in DEMO if necessary. Real-time spatial profiles of the kinetic quantities n_e, T_e, T_i, and to some extent of radiating impurities are expected to be available on ITER. Whether such profiles can be provided in a reactor environment is less clear. Real-time measurements of global quantities such as the plasma current and plasma pressure (beta), and of the plasma shape, will be available from magnetic sensors. Real-time measurements of the densities of reacting fuel species in the core are problematic, although some diagnostic capability is planned for ITER. Application of such internal measurements on DEMO appears difficult. Measurements of the fuel mix at the plasma edge, or in the divertor region using neutral emission (*e.g.* D_α/T_α) seems feasible, as does monitoring of the exhaust gas. Such measurements are expected on ITER and could probably be implemented on a DEMO. Alternatively, there may be some possibility of inferring the relevant core ratios from simultaneous observation of the 2.45 and 14.5 MeV neutrons arising from the $d(T,He^4)n$ and $d(d,He^3)n$ reactions respectively.

Issues for ITER

The nominal operating points for all the ITER standard scenarios are expected to be thermally stable[9]. However, for the inductive Q=10 H-mode case, small improvements in H-factor or confinement scaling, or extended operation at 17MA plasma current, could result in marginally unstable burn points around the nominal parameters P_{fus}=400MW, β_N=1.8, $<T_i>$=8.5keV. An example is shown in Figure 1. Control of the operating point in this range requires not only suitable actuators and control algorithms, but perhaps more importantly sufficient diagnostics and procedures to enable correct system identification. Note that the stability and sensitivity of the operating point depends sensitively on the details of the transport and radiated power, at a level which is unlikely to be available from *a priori* estimates of the physics. Examples of experimental determination of the stability and sensitivity of the operating point by suitable modulation of actuators and observation of the response of the fusion power, temperature, *etc.* is considered in [4].

For ITER operating at moderate β, excursions in the fusion power must be bounded at the extrema by the L-H transition threshold (including any hysteresis effect) on the low power side, and the effective power exhaust limits at the divertor plate on the high side. Given the lack of proximity to the β limit, loss of control is unlikely to result in disruption, but destabilization of ELMs or NTM could conceivably result from positive excursions in the fusion power.

In the case of ITER, even with Q≈10, substantial external heating power is still required at the burn point, and a control strategy for regulating the fusion power by modulation of P_{ext} seems feasible. This actuator has the advantage that the response would be on the energy confinement time scale, and is in some sense the most direct response to the power excursion driven by the thermal instability.

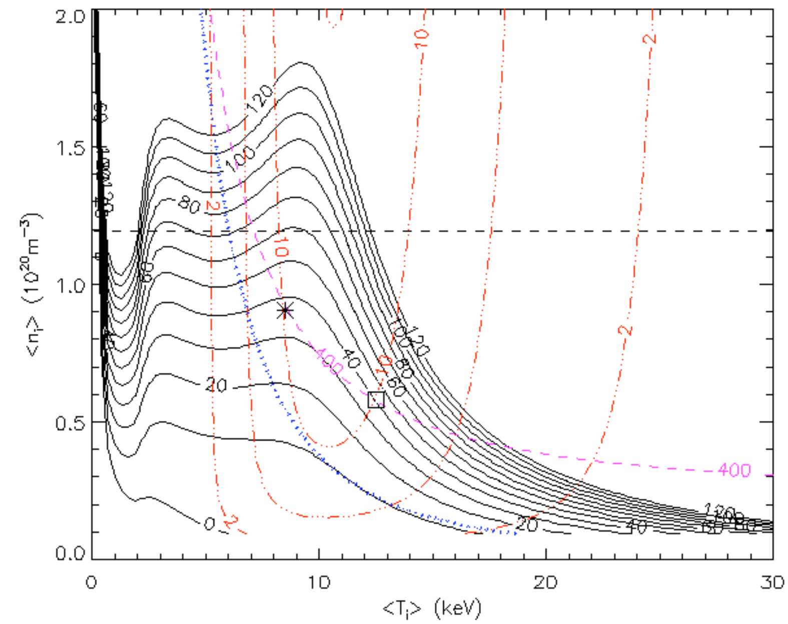

Figure 1. ITER Popcon with H_H=1.2. Solid lines are contours of constant external power; red chain-dash lines are Q; magenta contour is fusion power=400MW. The nominal operating point (asterisk) is marginally unstable. Stable operating point with same Q and fusion power is shown by open square. The dotted blue line represents the LH threshold; unless hysteresis is considered, contours to the left of this line are invalid.

Alternate solutions, of greater relevance to the near-ignited case, could also be developed. Use of the fuel feed (pellet injectors) as an actuator could be applied. A great deal of the available literature is based on the use of fueling either as the primary actuator, or in combination with external power. Reduction of the fuel ion density reduces the reactivity like $<n_{DT}>^2$, but the response to the fueling source (on ITER either pellet injectors or gas puffing) is on the somewhat slower particle confinement time scale. More importantly, reduction in the core density tends to reduce the radiated power fraction unless additional impurity seeding is provided simultaneously, thus aggravating the power exhaust challenge to the divertor. Conversely, positive excursions in the density to counter a decrease in reactivity are bounded by the proximity to the density limit. Despite these limitations, it seems likely that burn control based on net fueling could be successful in ITER.

An interesting alternative to variation of the density would be to control the fuel mixture (ratio n_D/n_T). Of course, it is normally considered appropriate to operate at the optimal 50:50 mix, where by construction the sensitivity of the reactivity to the mix vanishes to first order. However, operation at a slightly "lean" mixture of, say, n_D:n_T=60:40 reduces the reactivity by only 4%, and provides a finite (if rather weak) bi-directional knob for burn control that essentially leaves the plasma parameters unchanged, which could present a significant advantage, especially looking ahead to a highly coupled system operating close to numerous boundaries like an AT tokamak. As in the case of density control, the response time scale would be of the order of the main species particle confinement time. The concept could be tested on ITER using independently timed pellet injectors for D and T fueling.

An important issue is the ability to monitor the D:T ratio, especially in the reacting core. In ITER spectroscopic measurements should be available for the edge and divertor, but a core measurement is not assured. If the ion temperature is well characterized, then the ratio n_D/n_T may be inferred from the ratio of the 2.45 to 14.5 MeV neutron rates $R_{DD}/R_{DT} \sim (n_D/n_T)(\langle\sigma v\rangle_{DD}/\langle\sigma v\rangle_{DT})$. Alternatively it is possible that adequate determination of the fuel mixture could be obtained from observation of modulation of the fusion reactivity based on the impulse response to non-simultaneous injection of D and T pellets. If the pellet injectors are configured to modulate the fuel ratio about a nominal value $f_D=0.5$, for instance by using different injection frequencies, then feedback could be applied to maximize the amplitude of the second harmonic of the modulation. If the average mix is displaced from the optimum by more than the modulation amplitude then observation of modulations on the DD and DT neutron rates by phase sensitive detection techniques may provide a suitable measure. Additional comments on the influence of the fuel mixture can be found in a separate White Paper submitted by L. Baylor.

Another approach to burn control proposed for ITER[10] is impurity seeding, *e.g.* with Ar, to increase radiated power loss. An advantage relative to use of main ion fueling is that the same actuator serves to reduce the divertor heat load through main chamber radiation as it reduces the fusion power. The effective response time for impurity injection may also be somewhat faster than for the main ions. On the other hand, the impurity confinement time, especially in H-mode, is longer than that of the main ions, and impurity accumulation, particularly for recycling impurities, may be a serious issue. Moreover, under some circumstances the energy confinement is actually improved following impurity injection, which would tend to exacerbate the thermal instability.

Requirements and Resources for ITER

Burn control in ITER can be treated essentially as a SISO (or perhaps MISO) process, although some coupling to the power exhaust problem may be required. For the most part the operating point will be thermally stable, except for special cases and intentional exploration of unstable regimes, for example in support of control development for DEMO. The main issues are regulation within boundaries set by density limit, power exhaust considerations, and the H-L threshold. A choice of potentially suitable actuators is available, including external heating (NBI, RF), fueling (pellet injectors, gas puff), and impurity seeding (core and perhaps divertor). Sensors for the fusion power, radiated power, ion temperature, plasma (electron) density, and impurity content (spectroscopic) are available. Direct measurement of the core fuel mix may be problematic.

Development of control algorithms, including experimental system identification, must be pursued using integrated simulation tools plasma models, including both core and divertor, synthetic diagnostics and realistic source models for the relevant actuators. To some extent the building blocks for such a development platform are in hand. While simulation should be based on the best validated plasma models available, for purposes of algorithm development it will be necessary to allow for a range of possible plasma responses to account for unanticipated physics at the ITER scale.

To the extent possible, experimental validation of system identification and control algorithms should be carried out on existing experiments. Opportunities exist for simulating burn conditions using auxiliary heating to mimic the fusion source, as in experiments already carried out on JT-60U[11] and JET[12], which could be of use in qualifying some of the possible techniques. However, actual demonstration of burn control requires testing on a self-heated DT burning plasma, and will therefore need to be carried out on ITER itself.

Issues for DEMO

The problems of thermal stability and burn control in DEMO depend critically on what DEMO configuration is considered and what is being controlled. Here we consider the example of an advanced tokamak, similar to the ARIES-AT[2]. In contrast to the ITER case, the near-ignition (Q≅50), 90% bootstrap, high-β, advanced tokamak system presents a seriously constrained MIMO control problem. The only external power sources consist of current drive near the axis (FWCD) and near ρ=0.85 (LHCD), amounting to <40MW and supplying only 10% of the total current. The remaining ~350MW of loss power comes from the alpha heating. The pressure and current profiles are sensitively aligned to provide stability. The transport is driven by pressure and particle gradients and is assumed to be sensitive to magnetic shear as well as rotational shear. Aside from the current drive power, the only external inputs to the system are particle sources, including main fuel ions and some high-Z impurity seeding to provide enhanced radiated power to relieve the divertor heat load. Magnetic actuators are provided for shape control and MHD stabilization, including RWM and perhaps ELMs. NTM suppression would be provided either by LHCD or by ECCD.

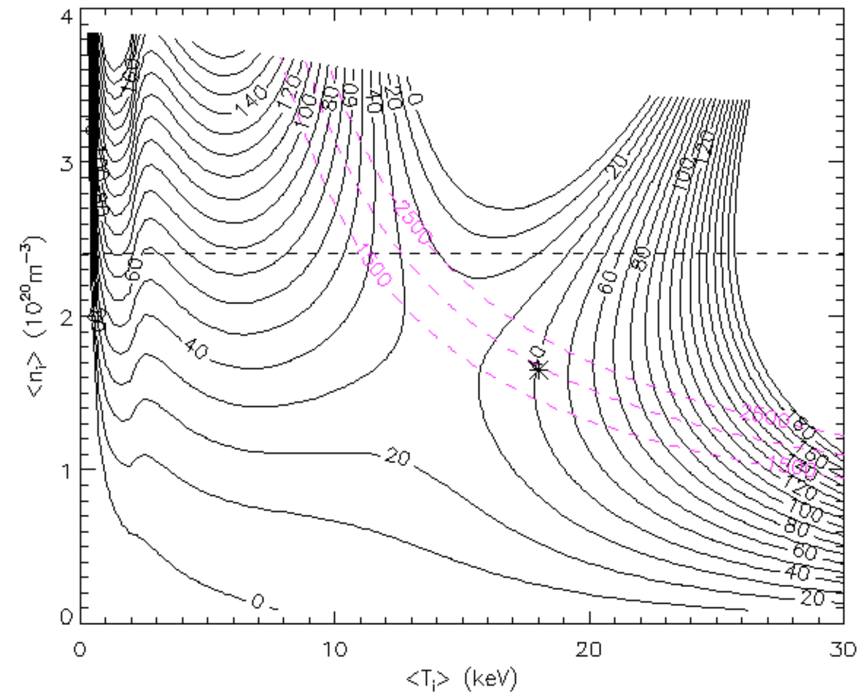

Figure 2. ARIES-AT popcon showing nominal operating point (asterisk) on high temperature side of contour. Confinement is scaled from ITER-89P with H_{89}=2.65.

The chosen operating point for ARIES-AT is explicitly on the stable side of the popcon (see figure 2), at relatively high temperature (<Ti~18kev>). This operating point is chosen to minimize the auxiliary power for current drive. The selection of the high temperature branch is driven by consideration of current drive efficiency, and is probably generic at least for a steady-state tokamak DEMO embodiment, implying that thermal stability might be assumed, i.e. the control issues are in regulation of P_{fusion}, and possibly in the approach (startup sequence) which might need to traverse the unstable range. The operating point is well above the L-H threshold, but above the no-wall β limit, implying active RWM stabilization is required.

Because the entire system is highly coupled, the 0-D POPCON picture is likely to be misleading, as is the formulation of the transport in terms of an empirical scaling based on L-mode physics. However, it is reasonable to assume that for a prescribed fixed equilibrium and transport a thermally stable operating point could be selected. The potential for instability could however arise from the highly coupled, self-organized nature of the system, or from disturbances that could displace the operating point into an unstable region. The most obvious example of instability in the coupled system can be described by considering an excursion in the reactivity which drives a pressure variation resulting in a change in the bootstrap current (or it's profile), which in turn modifies the transport. It is easiest to consider the 0-D situation where the total current is perturbed and the transport is assumed to be linear in the current as in the empirical scaling, but a local change in the magnetic shear even with perfectly controlled total current can have the same effect. In the simplest case, assume a gyrobohm-like scaling $\tau \sim I_p P^{-.6}$ and let $I_p \sim (nT)^{1/2}$ which leads to $P_L \sim (nT)^{5/4}$, which is slower than P_α out to quite high T_i, implying instability, albeit on the rather slow global current relaxation time scale. On a local level where the transport is governed in part by the magnetic shear an analogous instability could manifest on a somewhat faster time scale with no observable variation in the total current. Analysis of a high-bootstrap fraction reactor by Houlberg and Attenberger[13] with model transport coefficients based on ITER-89P found a stable operating point, and demonstrated effective control of the current by variation of the outer (LH) current drive power, a promising result. Experimentally, fully non-inductive high bootstrap plasmas were studied in DIII-D[14], which of course were not self-heated. They observed relaxation oscillations in plasma current (10%) and energy (20%) associated with formation of an ITB and subsequent excitation of MHD activity; the collapse phase of these oscillations is analogous to a large ELM, but with energy loss from the outer 30% of the plasma. It seems clear that such oscillations could not be tolerated in a DEMO environment, and some effective control must be provided.

The major problems for burn control in the case of DEMO arise from the paucity of available actuators, especially those that could counter a *negative* reactivity excursion, and the difficulty of observation of the internal configuration. Unlike on ITER, the diagnostic set on DEMO will be restricted to those measurements that are essential for control. The definition of this minimal set is lacking, and it is not obvious that even some of the likely items can be implemented.

If we assume that the operating point corresponds to a local maximum in the transport properties then the response to a negative reactivity excursion can be controlled only by the particle sources and perhaps an increase in CD power. Additional heating from the central CD source could conceivably compensate a small decrease in P_α on the relevant τ_E time scale, but not much dynamic range is likely to be available, and variation in the central q may be counter-indicated from the standpoint of transport or stability. Increasing the fueling could be expected to increase the reactivity at least as fast as n^2, but on the relatively slow particle transport time scale; this may be the most effective choice. In the case of smaller (relatively slow) excursions, variation of the fuel mixture may be the least perturbing intervention in terms of the plasma properties. In this case it would be necessary for the normal mix to be different from 50:50, perhaps as "lean" a mix as 70:30, which entails a 16% reduction in reactivity, allowing for compensation of reactivity excursions of that order. Note that the required increase in the nominal density to provide the same power output as for a 50:50 mix would be no more than 8%, probably less.

If an actuator is effective for a negative going perturbation it is likely also effective for positive excursions, *e.g.* reducing the density or fuel ratio, decreasing the on-axis power. However, since due to the proximity of the β limit a positive reactivity excursion is probably more dangerous,* some additional redundancy may desirable. An obvious candidates is impurity seeding to increase radiative losses, which as pointed out in the ITER context also has the salutary effect of reducing the divertor

* Actually, in the case of such a highly coupled self-organized system, it is not necessarily true that a decrease in reactivity would not also lead to changes in profiles resulting in excitation of a catastrophic instability.

heat load. Reduction of the outer current drive may be effective in reducing the total current and thereby the confinement on the long time scale, but may also be useful for manipulating the confinement by affecting the magnetic shear.

More exotic (and speculative) control techniques, especially for suppressing positive excursions by increasing losses, are conceivable. Assuming that some form of magnetic control for ELM suppression is being employed, the same coils may be used to modify the pedestal properties, and therefore the core confinement[15]; this would have the effect of transiently increasing the divertor heat load, and might require an increase in the divertor radiation. Application of magnetic braking to modify the rotation and thereby influence the confinement could also be considered, but this might adversely affect RWM stabilization. On a similar theme, one can imagine intentional excitation (or removal of suppression) of an NTM near mid-radius, reducing confinement transiently. Even more speculatively, the central current drive could be employed to modify q_0 so as to intentionally excite (or enhance) TAE modes (which would already be tending toward instability due to increasing β_α), leading to enhanced losses of fast alphas and removing part of the positive feedback driving the instability. The major drawback of this concept is the deleterious effect on the first wall of increased fast ion impact.

Requirements and Resources for DEMO

General considerations

Proper evaluation of the stability of DEMO against perturbations in the reactivity must be evaluated from a full profile analysis including dependences on the MHD stability and local transport, including particle and probably momentum transport. A physics-based evaluation is beyond present the present state of knowledge. While it was possible to design ITER on the basis of empirical scaling trends, this seems unacceptable for an AT high-bootstrap fraction DEMO (and not only from the standpoint of designing and validating the control system). Therefore, an ultimate requirement is the development of a physics-based, experimentally validated model of the advanced tokamak system. The key point here is not that such a step is required for the specific issue of burn control, but that the burn control problem is *in principle* not separable from the entire system and cannot be properly considered in isolation.

Development of the necessary knowledge base and simulation tools will depend on continuing development in the theory community, computational tools of the order of capability envisioned for the FSP[16], and, most importantly, rigorous experimental validation of the essential features. A large part of the experimental physics validation in highly coupled AT regimes can be carried out on existing non-burning tokamak facilities, including the new Asian super-conducting tokamaks, and on ITER "steady-state" discharges, which can provide a stringent test of the predictive models including the scaling to low ρ^*, response to self-heating, and energetic particle (alpha) driven instabilities. Unfortunately, ITER does not appear to capable of fully accessing the operating regime envisioned for an ARIES-AT style DEMO: it will not attain the necessary high values of β_N~5 and f_{BS}~.9, nor have sufficient β_α to fully address TAE drive. Nevertheless, from the standpoint of validating the physics basis underlying the DEMO design, ITER will provide the most stringent and relevant tests available.

Specific Considerations.

Preliminary (proof of principle) experimental testing of the efficacy of control strategies based on the some of the various potential actuators can be carried out on non-burning tokamaks operating in relevant non-inductive AT regimes using simulated burn methods analogous to those used in [11,12], allowing centrally peaked auxiliary heating to mimic the density and temperature dependence of the alpha power. Controllers based on fueling, central and outer current drive sources, and impurity seeding could in principle be tested in this manner, even in high bootstrap, high β_N conditions not accessible in ITER. Testing of techniques based on variation in fuel mixture would seem to require a DT capable facility, and is probably best carried out on ITER. Eventually any viable burn control technique should be validated under actual burn conditions in ITER. If the alpha power in the relevant scenario is insufficient (the nominal gain in the ITER steady state scenario is only Q=5), it may be necessary to adopt a similar strategy of controlling part of the auxiliary power to simulate near-ignition response even in ITER.

A minimal set of diagnostics suitable for system identification and control must be identified. Ruggedized and robust real-time diagnostics associated with proposed control schemes need to be developed. In particular, NBI-based diagnostics like CXRS and MSE will probably not be acceptable on DEMO. Furthermore, an unprecedented level of maintenance-free reliability, for periods of months to years, will be required. This will require a substantial development effort even beyond the program being carried out in support of ITER.

Since it is unlikely that the same level of detailed profile and fluctuation diagnostics employed on non-burning devices or even on ITER will be compatible with the environment, access, and reliability requirements of DEMO, high confidence in the validity of the models, or demonstration of insensitivity to possible modeling errors, is required. Sensitivity to quantitative discrepancies in model parameters can be evaluated computationally. However, qualitative errors, such as failure to include in the model a class of disturbances, will remain a concern. This implies that experimental testing under conditions as close to DEMO as possible, is a necessary step. Depending on how different the DEMO conditions are from those accessible in ITER, it may be necessary to conduct such testing on a new burning plasma facility embodying the same AT physics as DEMO.

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[1] W.A. Houlberg, et al., "Contour analysis of fusion reactor plasma performance", Nucl. Fusion **22** (1982) 935.
[2] S.C. Jardin, et al., "Physics Basis for the advanced tokamak fusion power plant, ARIES-AT", Fus. Eng. Des. **80** (2006) 25.
[3] O. Mitarai, et al., "”New control method of the unstable operating point in the FFHR Helical Reactor", Plasma and Fusion Res. **2** (2007) 021-1.
[4] O. Mitarai, K. Muraoka, "Ignition analysis and burn control and diagnostic developments for ITER", Nucl. Fusion **37** (1997) 1523.
[5] E.Rebhan, U. Vieth, "Burn stability and safe operating regime of a tokamak reactor with ITER scaling", Nucl. Fusion **37** (1996) 251
[6] E. Schuster, et al., "Nonlinear Lyapunov-based burn conrrol in fusion reactors", Fus. Eng. Des **63-64** (2002) 569.
[7] J. Mandrekas, W.M. Stacey Jr., "Evaluation of different control methods for the thermal stability of the international theremonuclear experimental reactor", Fus. Tech. **19** (1991) 57.
[8] W.Hui, et al., "Effectiveness and constraints of using the refueling system to control fusion reactor burn", Proceedings 15th IEEE/NPSS SOFE, Vol 2, (1993) 562.
[9] Y. Shimomura, et al., "ITER: opportunity of burning plasma studies", Plasma Phys and Contr. Fusion **43** (2001) A385.
[10] Y. Gribov, et al., "PIPB Chapter 8:Plasma operation and control", Nucl Fusion **47** (2007) S385.
[11] H. Takenaga, et al., "Burn control study using burning plasma simulation experiments in JT-60U", Fusion Eng. Des. **50** (2006) 76.
[12] T.T.C. Jones, et al., "Simulation of alpha particle plasma self-heating using ICRH under real-time control", 28th EPS Conf. on Contr. Fusion and Plasma Phys., Funchal, 2001, ECA **25A** (2001) 1197.
[13] W.A. Houlberg and S. E. Attenberger, "Evaluation of current drive requirements and operating characteristics of a high bootstrap fraction advanced tokamak reactor" Fusion Tech. **26** (1994) 566.
[14] P. A. Politzer, *et al.*, „Stationary, high bootstrap fraction plasmas in DIII-D without inductive current control“ Nucl. Fusion **45** (2005) 417.
[15] T. Petrie, *Private Communication* (2009).

[16] W. M. Tang, “Scientific and computational challenges of the Fusion Simulation Project”, Journal of Physics: Conference Series **125** (2008) 012047