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~~SUMMARY DISCUSSION:~~ AN INTEGRATED ADVANCED TOKAMAK REACTOR

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The tokamak concept improvement workshop addressed a wide range of issues involved in the development of a more attractive tokamak. The agenda for the workshop progressed from a general discussion of the long-range energy context (with the objective being the identification of a set of criteria and "figures of merit" for measuring the attractiveness of a tokamak concept) to particular opportunities for the improvement of the tokamak concept. The discussions concluded with a compilation of research program elements leading to an improved tokamak concept.

The Role of Fusion in Long-Range Energy Supply

The direction for tokamak concept improvement must be derived based on the projections of competing energy technologies in the mid-twenty-first century as well as on the features of a tokamak. Economic forecasts[1] suggests rapid world-wide population growth (a doubling by the year 2050), rapid economic growth in the developing nations (as much as 5% per year), possible inclusion of total life cycle costs in the pricing of electricity (reducing the competitiveness of fossil fuels), and increasing urbanization (contributing to the attractiveness of a central electric power source). Energy efficiency improvements will ameliorate the growing demand in the developed nations, while there will be a larger growth in those developing nations that will experience the greatest population and economic growth. However, the projections for energy demand are strongly dependent on geopolitics, ranging from an isolationist "castles and barriers" trend in which the developed nations restrict the deployment of technology to the developing nations to a "new frontiers" approach in which the developed nations export advanced technology for the improvement of the quality of life and stimulation of economic growth in the developing nations.

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[1] Garribba (this workshop)

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A variety of energy sources are expected to contribute:

- Fossil fuels, for which technology is available and partially deployed and for which finite and geographically localized resources are available now, produce atmospheric emissions (CO_2, NO_x, sulfur oxides, etc.) which are very costly to mitigate.
- Solar and renewables have a low "fuel cost" and enjoy popular support, but their resource availability is low, and their cost is now too large for many applications.
- Fission power, for which initial technology has been deployed and for which more attractive technology could be developed, suffers from public concerns about radioactive waste, radioactive release, and nuclear proliferation.
- Fusion Power has the following advantages: (1) universally available and virtually inexhaustible fuel supply, (2) negligible atmospheric emissions and limited impacts on ecological and geophysical processes, (3) low radiological hazards and waste levels, and (4) low risk of nuclear proliferation. Fusion power unfortunately has several disadvantages: (1) a 30-year development period leading to a demonstration fusion power plant, (2) large and expensive size for magnetic fusion program development steps (unless less integrated steps can be used or considerably higher confinement performance achieved), (3) large unit size (near 1000MW) contributing to the perception of low compatibility with present day utility structures, and (4) a radioactive waste volume comparable to that with fission power (but of significantly lower activity). There was considerable discussion about the question of whether fusion's advantage relative to fission should be highlighted or whether fusion should instead emphasize its similarities to renewable energy sources.

In the mid-21st century, with its availability of diverse energy sources as described above, several energy policies will significantly affect the attractiveness of fusion power:

- the demand for increased electrical power in the developing nations, which is strongly affected by the extent of involvement by the developed nations in the improvement of the status of the developing nations;
- inclusion of total life-cycle cost in the pricing of energy supplies, which would greatly increase the price of fossil fuels due to either the cost of sequestering carbon dioxide or "carbon taxes" imposed to discourage use;
- public acceptance of cost increases aimed at the amelioration of global energy impacts, such as due to the burning of fossil fuels;
- the structure of the electricity industry, wherein independent power producers would be more averse to large scale power plants than would utilities; and
- energy security concerns, which would be ameliorated by the development of an energy supply based on universally available fuels.

Historical records and many long-term energy supply models exhibit a sequence of growths of market share by new technologies and subsequent declines as they are displaced by improved technologies[2]. Discussions with utility executives[3] have shown several criteria which should be met for fusion power to gain a significant market share:

- cost advantage (at least 10%) over other available central station electricity generation options (note: the adoption of energy policies that either internalize total life cycle costs or include taxes to discourage environmental impacts would make a significant difference in the cost comparison with fossil fuels);
- ease of licensing (or the elimination of the requirement for licensing) and the absence of need for an evacuation plan, which would require minimal environmental impact and positive public perception (note: fusion's achievement of this criterion would likely require the development and use of fusion-specific regulations and terminology);

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[2] Garribba

[3] Conn

- no long-lived high-level radioactive waste (with waste lifetime being measured in units of human lifetime), which would require the development of low activation materials which could achieve a million-fold reduction in the radioactive waste activity; and
- a reliable, available and stable electric power source, which would require extremely low disruptivity and operation in very predictable and controlled modes.

Additional criteria which are desirable but not mandatory include the absence of a local or global atmospheric impact, a closed on-site fuel cycle, high fuel availability, capability for load-sharing, and availability over a range of unit sizes.

These criteria serve as yardsticks for measuring the attractiveness of tokamak concept modifications and thereby guide the concept improvement program.

Opportunities for the Improvement of the Tokamak Concept

Discussions of the present-day theoretical and experimental work on tokamak concept improvement included the assessment of:

- figures of merit for attractiveness,
- key configuration choices,
- relative advantages and disadvantages of steady-state versus pulsed operation,
- opportunities for higher reactivity through the achievement of higher plasma pressure in MHD-stable configurations,
- potential impacts on plasma transport and stability due to energetic particles such as alpha particles,
- directions for enhanced confinement, which would affect both the range of sizes of fusion reactors and the extent of control power needed to sustain the higher pressure stable configurations,
- technology improvements, which would increase the system performance, and
- improvements in the area of environmental and health attractiveness of the tokamak reactor.

These topics are discussed in subsequent sections.

Figures of Merit

Reactor studies have measured the reactor system attractiveness by criteria that include:

- high fusion gain, which is normally measured in terms of the triple product $n\tau T \sim (H\ I_p/\varepsilon)^2 \sim H^2\ (aB)^2\ (RI_p/(a^2B))^2$, which justifies the use of metrics such as (I_p/ε) and (aB) in making comparisons[4] ,
- high power density, which is translated into the highest level of $(\beta B^2)^2$, consistent with constraints on recirculating power and wall load[5] (note: the MHD physics aspects of this figure can be expressed as β^*/ε, since β/ε is the parameter in the MHD stability equations[6]),
- low recirculating power in steady-state reactors (which translates into $\varepsilon\beta_p \sim 1$ for the bootstrap current to carry most of the plasma current),
- low loop voltage for pulsed reactors,

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[6] Jardin

- long first-wall lifetime (neutron load <3 MW/m^2),
- extremely low disruption frequency (<3 per two years), and
- stability to high energy particle modes[7,8].

Key Configuration Decisions

In attempting to achieve these figures of merit, reactor designers are faced with several configurational decisions:

- steady-state versus pulsed operation,
- single-null versus double-null shape,
- plasma elongation (κ),
- triangularity (δ),
- helium fraction (which is really a particle confinement issue but is normally assumed independently in reactor studies due to the absence of an adequate predictive model),
- reliance on control of the plasma current density and plasma pressure profiles, and
- reliance on a close-fitting conducting wall for kink stabilization and the method for plasma rotation to make the resistive wall effective.

Steady-State versus pulsed Operation[9,10,11,12]

The choice of steady-state versus pulsed operation is based on both the relative availability of a physics basis for pulsed reactors and the projected cost advantage of steady-state reactors.

Pulsed reactors are perceived as having the following advantages:

- very efficient current drive (ohmic being ~500 times more efficient than radio frequency current drive),
- heating systems optimized for heating instead of having to also drive current, and

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[7] Kikuchi

[8] Romanelli

[9] Kikuchi

[10] Kadomtsev

[11] Jardin

[12] Lackner

- no need for a conducting wall for kink stability, since the ballooning mode is forecast to be destabilized before the kink mode, with stable operation at $\beta/\varepsilon \sim 0.12$ and $\beta^*/\varepsilon \sim 0.14$.

Steady-state reactors have more demanding physics requirements but have the following advantages:

- continuous operation, which permits higher magnet stresses, eliminates the need for inductive current drive coils and power supplies, and eliminates the need for between-pulse energy storage for continuous electricity output;
- possibility of lower-R/a, due to the elimination of the need for the ohmic transformer;
- greater control of the current profile, including the feasibility of enhance performance modes with higher-β_N and the elimination of sawtooth and fishbone instabilities by the avoidance of a resonant q=1 surface, and
- lower cost of electricity than for pulsed reactors.

MHD-stable High Pressure Plasmas

The discussion of MHD stability included three major topics: (1) theoretical predictions for advanced tokamaks[13,14,15], (2) experimental observations of opportunities for MHD stability[16,17,18], and (3) issues relating to higher pressure operation.

(a) Theoretical Predictions for Advanced Steady-State Tokamaks

Both theoretical and experimental studies have suggested that the plasma pressure limit is characterized by a limit on β which scales as the product I/aB, at least in the first stability region. The typical performance is limited by $\beta \sim 3.5$ I/aB, which gives higher β at smaller aspect ratio for a fixed-q[19]. Enhanced stability, indicated by higher Troyon coefficients (i.e., $\beta aB/I_p$), typically involves the achievement of second stability access over at least a

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[13] Wesson
[14] Jardin
[15] Chance
[16] Taylor
[17] Robinson
[18] Sabbagh
[19] Robinson

portion of the plasma profile. Theoretical simulations suggest that accessibility to higher performance (β >5 I/aB) regimes which requires more sophisticated plasma control of both the plasma shape and the profiles (of the plasma current density, pressure, and the plasma rotation) and a conducting wall. An issue is the feasibility of such advanced control in a reactor-like environment characterized by distant poloidal field coils and limited profile-control tools. A significant question revolves around whether the advanced profiles are readily achievable and sustainable with only modest control power; this relates to the issue of plasma confinement for such plasma configurations and whether such profiles are self-sustained by the self-heating and transport profiles.

The theoretical studies have clarified the characteristics for optimized performance:

- first stability to ballooning modes is facilitated by a peaked current profile and a broad pressure profile;
- second stability to ballooning is achieved with peaked pressure profiles, broad-to-hollow current density profiles, q_0>2 with avoidance of double tearing modes, and sufficiently triangular plasma shape; and
- stability to kink modes is achieved by appropriately tailored edge current and edge pressure profiles and effective wall-stabilization at high β_N.

Stability analyses[20,21,22] suggest that pulsed reactors should be able to operate at the ballooning limit without a conducting wall for the stabilization of kink modes, whereas steady-state reactors (which demand higher β_N) are expected to require a close-fitting conducting wall for kink modes stabilization.

Analyses of experimentally achieved high pressure profiles typically show that the experimental profiles are unstable to kink modes in the absence of a conducting wall. In contrast, theoretical predictions suggest that the resistive wall close to the plasma surface should stabilize the plasma modes only for a timescale of order that of the resistive diffusion time of the resistive

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[20] Chance

[21] Bondeson

[22] Okabayashi

wall. Evidently, there is some beneficial effect missing in the theory. This issue was addressed in several papers[23,24].

Theoretically, an infinitely conducting wall can stabilize kink modes if close enough and wide enough in extent on the large major radius side[25]; however, a finite conductivity wall is expected to permit the mode to grow in the absence of plasma rotation. Recent theories[26,27] suggest that plasma rotation may increase the effectiveness of a resistive wall if the wall is properly placed and if the plasma rotation is adequately fast. A "plasma mode" rotates with the plasma and is stabilized by a close fitting wall and an adequately rotating plasma due to a combination of effects such as coupling to sound waves and ion Landau damping, perturbed currents in the cold plasma mantle, and edge plasma inertia and viscosity in the mantle. A "resistive wall mode" locks to the wall, grows on the resistive timescale of the wall, and is stabilized only if the wall is sufficiently distant. This combination of modes raises the question of whether there is a window of stability between a wall being too distant to stabilize the plasma mode and too close for wall mode stability. Future directions of research should include assessments of the resistive wall modes and refinements of the requirement for plasma rotation; current projections require that the plasma rotate at 10% of the Alfven speed, which is nearly unachievable in reactor-relevant plasmas.

If the stabilization by plasma rotation and a resistive wall is ineffective, high performance regimes would still be available if the kink mode could be stabilized by active feedback. Such development would be challenging but would likely involve a resistive wall to slow the growth of the mode to a manageable rate and either magnetic forces from helical coils or pondermotive forces from a helical arrangement of antennae or localized current drive phased to the observed mode.

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[23] Chance
[24] Bondeson
[25] Chance
[26] Bondeson
[27] Jardin

(b) Experimentally Observed Opportunities[28,29,30,31,32]

Experimentally, plasma performance significantly beyond the theoretical Troyon limit ($\beta \sim 2.8$ I/aB) has been achieved, largely due to tailoring of the plasma profiles (mostly the current profile) and the action of nearby stabilizing conducting structures. The β-limit is seen to typically increase with peaking of the current density profile ($\beta \sim \ell_i$ I/aB) and broad pressure profiles in DIII-D, TFTR, and JT-60U. $\beta > 6$ I/aB has been obtained transiently by peaking of the current profile by a negative current ramp. In many devices (e.g., DIII-D) pressure gradients seem to be limited by marginal stability to high-n ballooning modes. A concern about this high-ℓ_i mode is that peaking of the current profile may be difficult to sustain in steady-state due to the broadening influence of the bootstrap current, which is expected to carry the bulk of the plasma current in order to keep the recirculating current fraction within bounds; for these high-ℓ_i modes steady-state operations will likely demand a rather extensive current profile control capability. In such regimes the performance is limited by a variety of instabilities such as low-n external kinks, 1/1 fishbones, and 2/1 and 3/2 modes at β-collapse. Since the high-ℓ_i mode involves such a peaked current profile, one is naturally concerned with the stability due to the low central safety factor (q_0); future theoretical analyses should address the issues of observed high performance in plasmas for which a significant portion of the plasma is below $q=1$.

Experimentally, the theoretically predicted kink mode seems to be somewhat stabilized in cases with resistive walls and adequate plasma rotation. Confidence in resistive wall stabilization would be gained by the demonstration of a doubling of the β-limit with high plasma rotation.

Experiments on low aspect ratio devices such as START[33] and the extrapolation of trends (for instance $\beta \sim 12\%$ in DIII-D's 2.7 aspect ratio compared to 6.8% in PBX-M's 5.5 aspect ratio) motivate the exploration of high

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[28] Taylor
[29] Sabbagh
[30] Jardin
[31] Okabayashi
[32] Robinson
[33] Robinson

performance in devices with aspect ratio (R/a) below 2. Experiments to-date have already demonstrated the achievability of high-β in first stability, good confinement, absence of major disruptions, natural elongation (1.2 to 4.0) and high shear, and natural divertor action. Theoretical analyses suggest that stability is limited by ballooning modes rather than kink modes (possibly reducing disruptivity) and suggest that high pressure-driven currents (both bootstrap and diamagnetic) could permit steady-state operation with plasma currents roughly 1.7 times the current through the center toroidal field coil. Reactor studies have suggested the feasibility of an attractive reactor using only conventional (resistive) coils. Theoretical studies of the magnetic configuration suggest the potential for improved confinement since the magnetic field is nearly constant on flux surfaces, the banana tips are in a good curvature region, etc. Such forecasts raise the intriguing question of whether low aspect ratio tokamaks might afford a lower cost development path for the demonstration of fusion power.

(c) Issues Relating to Higher Pressure Operation

Assessment of the theoretical and experimental evidence presented at the workshop suggests several issues relating to higher pressure operation:

- Pulsed reactors appear to have a relatively solid physics basis, whereas steady-state reactors demand significant improvements in the tokamak concept.
- Significantly enhanced performance seems to require significant elongation and triangularity of the plasma cross section. Discussions at the workshop suggested that double-null configurations are maintainable and that arguments of the infeasibility of double-null reactor concepts need reassessment[34].
- There seem to be two distinct directions to advanced tokamak development: (1) a high-ℓ_i mode wherein the narrow profile is achieved today by ramping down the plasma current and for which the plasma pressure is limited by $\beta \sim 4 \ell_i$ I/aB, and (2) a low-ℓ_i mode characterized by a very broad or even hollow current profile and in which a portion of the plasma cross section has access to second stability. A significant issue is the extent to which the profiles are self-sustaining based upon the self-heating and transport profiles. For the

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[34] Conn

low-ℓ_i mode, the broad pressure profile seems consistent with a large fraction of bootstrap current and improved confinement. For the high-ℓ_i mode, there is a concern that the large fraction of plasma bootstrap current, which is necessarily broad, may tend to broaden the plasma current profile despite central current drive and may also suffer from instabilities related to the q=1 resonant surface.

- Stabilization of kink modes by a resistive wall and achievable plasma rotation is a very significant issue. The theoretical prediction of a wall mode raises the specter of a wall too close to the plasma. The present day theoretical estimates suggest that an unachievably large plasma rotation may be required. If kink mode stabilization by a resistive wall in plasma rotation proves unachievable, then the high performance modes may require challenging feedback stabilization.

Effect of Energetic Particles[35,36]

Recent reactor studies have generated reference profiles which have been shown to be theoretically unstable to energetic particle modes, thereby motivating both theoretical and experimental assessments of stability thresholds and transport.

- Low frequency modes such as sawteeth are weakly unstable and can be stabilized by a modest β_{hot}. Sawteeth should be more easily stabilized in present day machines than in reactor-relevant devices such as ITER. In contrast, fishbone modes can be destabilized by a modest β_{hot} particularly if the radius of the q=1 surface is large, as forecast for ITER. Fishbones with resonant frequency near the diamagnetic frequency of 200 keV alpha particles might be used for helium ash removal.
- High frequency modes (such as the toroidal alpha eigenmode and the kinetic toroidal alpha eigenmode) have linear stability thresholds that depend on a variety of effects and maybe to either stable or unstable in devices such as ITER. Saturation mechanisms and transport must be assessed.

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[35] Romanelli
[36] Kikuchi

Enhanced Confinement Plasmas

Workshop discussions of enhanced confinement regimes focused strongly on (a) whether the enhanced confinement modes are expected in the regimes of enhanced pressure capability and (b) whether the profiles in the enhanced pressure plasmas are expected to be self-sustaining and consistent with steady-state operation with low control power. The physical bases for the enhanced confinement modes were emphasized over the typically-transient control techniques currently used to achieve the modes. As such, it divided into H-like and non-H-like modes[37].

Most reactor designs assume enhancements of the confinement above L-mode; for example, the reference ITER does not ignite at L-mode confinement and requires confinement factors nearly twice that of L-mode. The experimentally reported enhanced confinement modes can be characterized as an "alphabet soup", involving some combination of the control technique used for access and some indication of similarity to the high confinement H-mode. More physical would be a classification based on the types of profiles and the boundary conditions; along that line, enhanced confinement has been observed in density profiles ranging from peaked (such as in supershots) to broad (as in H-mode), temperature profiles ranging from peaked to broad, and current profiles ranging from peaked (as in the high-ℓ_i mode) to hollow (as in the PEP and reversed central shear modes), and fast particle fractions and profiles ranging from low fraction to high fraction (as in the high-T_i mode) and peaked-to-absent profiles. The boundary conditions are also quite varied, ranging from moderate to ultra-low recycling (as in the supershot mode), with radiation cooling of the edge ranging from low to high, edge gradients from moderate to large, and the plasma current density, plasma temperature, plasma density, and poloidal velocity and edge electric fields ranging from natural (as in the H-mode) to driven (as in biasing experiments). The extrapolability of the enhanced confinement modes to steady-state reactors is also varied depending on their compatibility with edge requirements (in particular, consistency with high-edge density required for radiation either from a plasma mantle to the first wall or from the scrape-off layer to the divertor channel), and impurity accumulation. The

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[37] Lackner

workshop examined the patterns and the extrapolability to a reactor-relevant regimes.

- H-mode enhanced confinement has been demonstrated on most (if not all) X-point tokamaks with auxiliary heating power, with confinement enhancements ranging from 1.5 to 2.5 relative to L-mode. More enhanced confinement has been observed in a variety of modes (VH, PEP VH, Hot-ion VH, High-β_p VH modes, etc.), with confinement enhancements of roughly 4. Scalings independent of the L-mode multiplier are emerging, however these forecasts need refinement since they forecast unphysical situations such as the ELM-free modes having lower confinement than the ELMy modes at reactor conditions. The physical basis for the H-modes is emerging as relating to the shearing of the turbulent eddies by a strongly sheared radial electric field drift in the edge plasma and associated suppression of turbulent fluctuations, leading to a transport barrier near the edge at the location of the sheared electric field. Enhancement of core confinement, however, is not understood. Compatibility of H-modes with reactor conditions is somewhat mixed: (a) ELM-free modes are not stationary and hence do not extrapolate to a reactor. (b) Type-I H-modes have been shown to be stationary and extrapolable, however there are some concerns about the capability of divertors to handle strong bursts of power associated with the ELMs and about the adequacy of the ash and impurity removal. (c) Other types of H-modes are observed in other regimes and there is a concern about whether or not the type of ELM can be adequately controlled in a reactor. (d) A concern was raised regarding the kink stability of reactor profiles with a transport barrier at the edge, due to the large edge bootstrap current driven by the large gradient[38].
- Non-H enhanced confinement modes have been observed and typically relate to either extremely broad or extremely peaked profiles of the plasma current. The high-ℓ_i mode has shown confinement enhancements of a factor of 3 and at high-β_N. Pellet enhanced performance (PEP) modes, seemingly with reversed shear, have shown confinement enhancements of 2 to 3. High-β_p plasmas[39], driven by

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[38] Kikuchi

[39] Sabbagh

neutral beam current drive with $q_0 \sim 2.5$ and with lithium pellet conditioning of the limiters and DT plasmas, have shown enhancement factors of greater than 4 relative to L-mode, $\beta_N \sim 3$, 50% non-inductive current drive (a combination of neutral beam and bootstrap current), 35% bootstrap fraction and second-stability access. Supershots[40] have shown high reactivity, but there are concerns about the compatibility of the low recycling and the divertor boundary requirements. The PBX-M CH-mode, in which a transport barrier seems to exist at the radius of the ponderomotive force due to IBW deposition, seems to suggest an intriguing possibility of control of the transport profile, which may be the only means for pressure profile control when self-heating is dominant. Electrostatic biasing experiments (by electrodes, limiters and divertor biasing) have shown that the edge electric field can be influenced, leading to changes in poloidal rotation, reductions of the scrape-off layer width, reductions of the H-mode power threshold, reductions of fluctuation level, plasma flow to the divertor with increased pumping and impurity control, and control of the divertor plate power distribution.

The discussions on enhanced confinement raised considerable issues. Discussions of the benefits of enhanced performance suggested that the primary advantages of enhanced confinement are a reduction of the power plant's unit size and the possibility of more affordable development steps[41]. The primary focus of the workshop's discussion on enhanced confinement related to the consistency between the high pressure, high performance regimes and the self-sustainment of the required profiles, illustrating a strong linkage between enhanced confinement and high pressure stability for reactor relevance. The modes were classified based on profile attributes rather than transient access techniques[42]:

- H-and VH-modes were discussed extensively by several speakers[43,44] and seem to be consistent with enhanced confinement within regions of large poloidable velocity shear with the spatial extent of

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[40] Sabbagh
[41] Conn
[42] Lackner
[43] Zohm
[44] Thomsen

enhancement corresponding to the radial width of the sheared flow region. These discharges exhibit very high confinement and a high edge density, consistent with the needs for edge radiation and divertor performance. However, there was a concern about the instability of kink modes driven by the edge localized bootstrap current driven by the localized gradient at the edge[45].

- Reversed shear modes (JET, PEP, TS LHEP, JT-60U, ...) are possibly due to reduced transport in regions of negative shear. Such a hypothesis is motivated both by the improved confinement observed in such configurations and by theoretical predictions such as by Rewoldt and Tang[46]; however, there was concern that reversed shear may not be sufficient for enhanced confinement, as evidenced by "un-enhanced" confinement in JET and FT-U. Reversed shear enhanced confinement modes are consistent with MHD-stability (second-stability requiring the negative shear which is a natural consequence of the off-axis bootstrap current). Impurity and helium accumulation in the stable core plasma are issues.
- High-ℓ_i modes (such as in current ramp down experiments on TFTR, DIII-D, JT-60U, ...), seem correlated with reduced transport in regions of large positive shear. Such enhanced confined profiles are consistent with first-stability enhanced confinement ($\beta \sim \ell_i I/aB$) and consistent with central current drive (since they are related to high current in a very small area at the core). There is a concern about the inconsistency of the high-ℓ_i profiles with the much broader bootstrap current profile and a concern about the requirement for a relatively high-q_{edge} in order to keep q_0 modestly below 1.
- Peaked density modes were discussed, but there was no consensus on the mechanism responsible for the enhanced confinement. These modes have demonstrated enhanced central reactivity; however, they do not make effective use of the large plasma volume outside of the peaked core and may be inconsistent with the high edge density requirement for power handling by either a plasma mantle or a divertor. There is concern about impurity and helium accumulation, although a peaking

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[45] Kikuchi

[46] Jardin

of the helium profile and a hollowing of the fuel profile is not undesirable[47].

- High-T_i modes were discussed but the mechanism for the enhanced confinement was not suggested and compatibility with the divertor was a concern.

Technology Improvements[48,49,50]

While physics performance is a necessary requirement for the success of steady-state tokamaks, equally important are developments that contribute to the technical performance of the tokamak. While not the main focus of discussions within the workshop, there were significant contributions:

- Magnets, particularly toroidal field magnets, would benefit from the development of improved superconductors. Since the reactivity of the plasma scales as B^4, affordable high-field magnets would be a great opportunity for improvement of the viability of attractive tokamaks.
- Plasma-facing components (such as in the first wall and the divertor) demand the development of materials such as carbon-carbon composites, beryllium-coatings, and high-Z materials. Material performance after irradiation must be determined, since neutron wall load is a determining factor, with the lifetime of the first wall limited to roughly ten years (100 to 200 displacements per atom).
- Heating and current drive systems are the main source of recirculating power and so improvements of their efficiency would increase the overall efficiency of the power plant. While only conventional current drive techniques were discussed in the workshop, speculative possibilities such as helicity injection were mentioned.
- Structural and protective materials must be developed and characterized for their mechanical performance, heat transmission, neutron damage (which eliminates austenitic steels and causes concerns for ferritic marstenitic steels), and activation level and lifetime. Studies on vanadium and silicon carbide composites, remote handling, and availability (both reliable operation and disruption avoidance) were suggested.

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[49] Kikuchi

[50] Andreani

Improvements Related to Environmental Safety and Health Attractiveness of the Tokamak Reactor

As discussed in the advice from utility executives[51], the elimination of long-lived high-level radioactive waste is a significant component of the attractiveness of fusion. As such, low activation materials such as vanadium and silicon carbide composites should be developed. In the longer-term (after the deployment of the initial deuterium/tritium reactors), advanced fuel cycles might be envisioned, involving deuterium and helium-3, and the catalytic burning of deuterium by re-injection of tritium and helium-3[52]. Catalytic burning has the advantages that the reaction products are burned at the same time as the deuterium, that there is no need for tritium handling or a breeding blanket, that direct conversion is more feasible (with 60 percent of the fusion power produced as charge particles, but there is a concern about the significant fraction of bremsstrahlung radiation), and that there is less divertor power loading. There is, however, a disadvantage in that confinement requirements are much more demanding for catalytic burning, with an $n\tau$ needing to be ~20 times that for the DT reaction.

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[51] Conn

[52] Bickerton

Research Program Leading to the Improved Tokamak Concept

Assessment of the technical concerns raised by the theoretical and experimental studies of enhanced confinement and stability and of the extrapolability to reactor conditions have identified several areas for research leading to the development of an improved tokamak concept.

Pulsed Reactors

Pulsed reactors have considerably less flexibility in control of the current profile than steady-state reactors due to the absence of auxiliary current drive systems. As such, the plasma performance is expected to be lower; much less physics R&D is needed to achieve their projected level of performance. The research and development needs are dominantly in divertor and power handling concepts and disruption avoidance and amelioration. In these and other respects, the necessary physics R&D is listed in the ITER Physics R&D Needs document.

Steady-State Reactors

The additional flexibility afforded by steady-state reactors with their increased control capability demands considerably more physics research and development. This development can be broken into three areas of increasing complexity: (1) open-loop plasma control tools, (2) integrated-control high-performance plasmas, and (3) demonstration of reactor-relevant advanced tokamak performance.

(1) Open-Loop Plasma Control Tool Development[53, 54, 55,56]

Steady-state reactors with enhanced confinement and stability performance benefit from flexibility in the current density profile. Central current drive is applicable both to the high-ℓ_i mode where there is a need to drive substantial central current to achieve the high-ℓ_i and to the reversed shear core mode where the profile benefits from control at both the center and off-axis. Off-axis current drive is most applicable to the reversed shear core mode where control of the minimum-q position is desired. However, due

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[53] Jacquinot
[54] Tonon
[55] Kikuchi
[56] Moreau

to the cost of the recirculating power, there needs to be a balance between the enhanced flexibility available with extensive current drive and its cost. Bootstrap currents of 60% to 80% can likely be afforded with 20% recirculating power. The figures of merit for auxiliary current drive are the physics efficiency $\gamma = n_e R I_{CD} / P_{CD}$ and the electrical efficiency $\eta = P_{CD}/P_{electrical}$. Other figures of merit relate to compatibility of the current drive system with the reactor environment, radiation compatibility, neutron shielding impact, survivability with disruptions, and functionality for both heating and current drive.

Attributes of the various current drive methods were described[57]:

- Lower hybrid (for off-axis current drive) is projected to have high overall efficiency but needs an advanced launcher and would benefit from improvements of the electrical efficiency. Penetration is an issue relating to both wave damping and accessibility except for edge current drive.
- Fast wave current drive (for central current) has moderate overall efficiency and good electrical efficiency. There are also opportunities for more localized current drive at ion cyclotron resonance.
- Neutral beams (for a broad central drive) has moderate overall efficiency, although developments of beam energy and electrical efficiency are suggested. There is a concern about Alfven waves being driven unstable by high energy beam particles, with the high energy being required for adequate penetration.
- Electron cyclotron current drive (at resonant positions) allows flexibility in the position if the frequency were tunable or the optics flexible. Unfortunately, ECCD suffers from low overall efficiency and limited tunability. However, this concern is somewhat compensated by ECCD's compatibility with the tokamak structure and its potential for localized current drive for MHD stabilization.

There was considerable discussion about the desirability of profile control by 2-point control: One system driving current at the center and one driving current off-axis; however, the benefits of this flexibility must be balanced by the cost.

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[57] Tonon

Bootstrap current was shown to be predictable due to agreement of neoclassical theory with resistivity and bootstrap current profiles in large tokamaks[58]. The bootstrap current is not driven exclusively by the density gradient but by more general forces; a combination of formulation is needed to adequately model the bootstrap current. While there was a concern related to the MHD stability of plasmas dominated by bootstrap current, a simulation of a stable plasma with $q_0>2$ at modest elongation was shown. A neoclassical dynamo may drive the seed current for bootstrap dominated profiles[59].

While the pressure profile control figures prominently in MHD equations, its control may not be feasible. Deep fueling was shown to be difficult both due to the challenges of developing and applying high velocity pellets[60] and due to the energetic penalty of neutral beam fueling[61]. A possibility for modest pressure profile control may be afforded by speculative techniques such as inducing sheared rotations at specific layers within the discharge[62, 63].

A significant addition to the tokamak reactor concept discussed at the workshop was the requirement or desirability of control of the plasma rotation profile. Three objectives were cited:

- Kink stabilization with a resistive wall may demand plasma rotation as high as 10% of the Alfven speed. Achieving this rotation speed will be challenging since neutral beams with adequate penetration and modest (50 MW) power would not drive that level of rotation, nor would radio frequency waves of similar power.
- Enhanced edge confinement seems to be linked to the achievement of a sheared poloidal plasma flow, requiring either adequate heating or the application of external bias.

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[58] Kikuchi
[59] Bhattacharjee
[60] Stork
[61] Conn
[62] Thomsen
[63] Okabayashi

- Pressure profile control in self-heated plasmas may be achievable with core rotation shear driven by high momentum waves such as Ion Bernstein waves.

(2) Integrated-control of High-performance Plasmas

The high-confinement and stability performance of steady-state plasmas will require predictable control of profiles and shape. Such control demands a characterization of the plasma response to both the stimuli (i.e., the modification of the plasma profiles by the controllers such as radio frequency waves) and the plasma responses to the profiles (modification of the stability and transport behavior). These characterizations of the plasma response need to be integrated into a feedback control system for the profiles and plasma reactivity, including the complexities of the system responses such as delays and nonlinearities[64].

(3) Demonstration of Advanced Tokamak Performance

The end result of the physics developments will be demonstration of tokamak plasmas extrapolable to a reactor. There are two areas of significant concern and opportunities for near-term development:

- Demonstration of plasmas with appropriate figures of merit such as high-β^*/ε, $\varepsilon\beta_p \sim 1$, $P_n/A \sim 3$ MW/m^2, extremely low disruptivity, adequate ash and impurity removal, and adequate power handling (by either divertor or plasma mantle), and confinement that leads to largely self-sustaining profiles in reactor-like conditions.
- Assessment of the effectiveness of high-β kink stabilization by a resistive wall with plasma rotation. If stabilization can be achieved by a resistive wall with achievable rotation then such configurations are reactor relevant; otherwise, either pulsed reactors or feedback stabilization of kinks may be required.

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[64] Moreau

Achievement of Fusion's Potential

Returning to the criteria necessary for fusion to gain a significant "market share", there are two audiences to which fusion's advantages must be demonstrated:

- The public, both in its perception of energy issues and its governmental policies, should consider the impact of energy production on global environmental concerns and include the total costs for energy in its decision making. Fusion would be more competitive if the public accepted increased cost in order to mitigate global environmental damage and to increase energy security.
- The boards of directors must be convinced that fusion has significant advantages, such as a 10% cost advantage (achieved by both high physics performance and high magnetic field), ease of licensing and regulation (by obvious environmental and health and safety advantages), no high-level long-lived radioactive wastes (by the development of low-activation materials), reliability and availability (by appropriate levels of operational control and disruption avoidance), and preferably a capability for load-following and a range of sizes.

In summary, the workshop succeeded in deriving research program elements based on an assessment of both the criteria for an attractive reactor and the opportunities suggested by theoretical and experimental work on advanced tokamaks. Achievement of the suggested physics and technology programs has a good probability of satisfying the concerns of both the "public" and the "boards of directors" and making the improved tokamak attractive.