MEETING REPORT

SUMMARY OF THE WORKSHOP ON ALPHA-PARTICLE EFFECTS IN THE ENGINEERING TEST REACTOR, GERMANTOWN, MARYLAND, JUNE 15–16, 1987

INTRODUCTION

Much has been gained in understanding the role of alpha particles in tokamak reactors since Kolesnichenko reviewed the subject in 1980 (Ref. 1). The Göteborg symposium on the role of alpha particles in magnetically confined plasmas updated the progress in 1986 (Refs. 2 and 3). The objective of the present workshop was to further elucidate alpha physics in tokamak reactors by bringing together 30 experts in the field and to identify Engineering Test Reactor (ETR) alpha physics issues for program planning by the U.S. Department of Energy (DOE). The meeting was organized by G. H. Miley (University of Illinois) under the auspices of the Ignition Physics Study Group of the Compact Ignition Tokamak (CIT) project and the U.S. International Thermonuclear Experimental Reactor (ITER) studies. L. M. Hively [Oak Ridge National Laboratory (ORNL)] was the meeting coordinator. D. J. Sigmar [Massachusetts Institute of Technology (MIT)] chaired the final panel that drew together all of the findings and recommendations for this summary. This report contains the salient points of the workshop papers; complete papers from the workshop appear in this issue of *Fusion Technology* after this summary.

The workshop was divided into six sessions:

1. overview
2. slowing down and instabilities
3. ripple trapping and losses
4. alpha ash transport and control
5. burn control
6. alpha physics data base and ETR design implications.

Subsequent sections of this report describe each of these sessions in turn.

OVERVIEW

The first session provided an overview of the context of program planning, international research, and the scope of alpha physics issues. R. J. Dowling (DOE) described present ETR research and the prospects for international collaboration on ITER. L. J. Perkins [Lawrence Livermore National Laboratory (LLNL)] discussed the design parameters, philosophy, and phases of machine operation. L. M. Hively (ORNL) explained the workshop objectives and summarized the alpha physics issues (see Table I).

D. J. Sigmar (MIT) addressed the self-consistency of resistive tokamak plasmas at ignition, as constrained by ideal magnetohydrodynamic (MHD) stability at finite beta. For an ohmically driven current, MHD stability requires that the electron temperature profile be much flatter than parabolic for times longer than the skin time. However, this requirement conflicts with the ion temperature profile being more peaked than parabolic due to the large amount of fusion-generated alpha heating in the core. The conflict is exacerbated when beta is close to the MHD stability limit and therefore argues in favor of large aB^2 designs. Applying current drive and electron cyclotron resonance heating (ECRH) sources may mitigate the problem. This area needs substantial development.

SLOWING DOWN AND INSTABILITIES

B. Coppi (MIT) discussed alpha fishbone oscillations arising from an internal, ideal $m = 1$ mode centered at $q = 1$, which is finite Larmor radius stabilized in the absence of dissipative terms. However, the trapped alpha precessional resonance provides a destabilizing effective viscosity, allowing alphas to slow down to ~400 keV before they are resonantly lost. The scattering of these intermediate energy particles should not degrade the alpha-particle heating power significantly. On the other hand, the nonresonant loss of the 3.5-MeV alphas in the fluctuating field associated with this instability may have more serious consequences. This theory contrasts with the Princeton fishbone theory, which predicts direct, resonant, fast alpha losses near 3.5 MeV.

J. W. van Dam (Institute for Fusion Studies) summarized the global Alfvén eigenmode, the shear Alfvén gap mode, and the ballooning mode; simple estimates show that all are

TABLE I

Summary of Findings from MFAC Panel XIV (February 1986) and from This Workshop

	TFTR (D-T)	CIT	ETR	MFAC-XIV[a] Criticality × Uncertainty	Workshop Criticality[b] × Urgency[c] × Uncertainty[d]
Single-alpha particle					
Confinement	x			1 × 3	1 × 1 × 3
Slowing down	–	x		1 × 3	1 × 1 × 3
Finite-alpha component					
Microinstabilities	–	x		2 × 2	2 × 2 × 2
Macroinstabilities	–	x		1 × 2	1 × 1 × 2
Pellet fueling	–	x		3 × 2	3 × 3 × 2
Induced E_r	–	x		2 × 3	2 × 2 × 2
Alpha heating					
Thermal transient	–	x		1 × 2	1 × 2 × 2
Sawtoothing effects	–	x		1 × 2	1 × 1 × 2
τ-E scaling		x		1 × 1	1 × 1 × 1
Beta limit effects		x		2 × 2	2 × 2 × 2
Burn control					
Profile evolution		–	x	1 × 2	1 × 1 × 1
Thermal stability		x		1 × 2	1 × 2 × 1
Long-term control		–	x	1 × 2	1 × 3 × 1
Particle control					
Ash buildup/control		–	x	2 × 2	2 × 2 × 1
Fuel burnup		–	x	2 × 2	2 × 1 × 1
Impurity control		–	x	2 × 2	2 × 2 × 1

Note: Moving left to right, "x" indicates the first experiment where the issue will be addressed, and "–" indicates that some limited information may be obtained in this device.

[a]Here, 1 is most critical or uncertain and 3 is least critical or uncertain.
[b]Here, 1 = affects feasibility of design to meet ETR goals, 2 = affects usefulness or acceptance of conceptual design, 3 = affects engineering design of ITER, and 4 = affects operation of ITER.
[c]Here, 1 = needed before conceptual design, 2 = needed before start of construction, and 3 = needed before operation.
[d]Here, 1 is most uncertain and 3 is least uncertain.

destabilized by alphas. Scaling of these modes favors a small tokamak with a large aspect ratio. A transition to second stability is theoretically possible using huge amounts of auxiliary heating power (150 MW to 23 GW) for short periods to move through the unstable region between first and second stability (unrealistic for ETR). This scheme depends on the existence of a soft beta limit where the unstable ballooning modes have an increased (but finite) thermal conductivity.

W. M. Nevins (LLNL) found no loss-cone instability when all the trapped alphas are ripple lost from a plasma with no magnetic field gradient. Previously, the magnetosonic wave had been found essentially stable. Also, the shear Alfvén wave is difficult to destabilize by alpha-particle velocity space effects. G. H. Miley and coworkers (University of Illinois) have come to a similar conclusion independently, finding velocity-space inversion conditions difficult to achieve in Tokamak Ignition/Burn Experimental Reactor (TIBER)-like ETRs.

D. A. Spong (ORNL) presented numerical results for moderate-to-high-n ballooning modes that are destabilized by the trapped alpha precessional resonance in the Tokamak Fusion Test Reactor (TFTR), CIT, and ETR. A tentative conclusion is that plasma stability improves as elongation increases from 2 in CIT (with a critical beta of 1%) to 2.4 in ETR (with a critical beta of 3%). Further checks of the shooting code are necessary to assure convergence to the proper eigenvalue and to ascertain the correct dependence of the boundary conditions at large values of the extended poloidal angle variable. The overall trend is toward lower critical beta due to the alpha precessional resonance. This mode is the high-n version of the fishbone instability.

The subsequent discussion among the experts resulted in the following conclusions:

1. Alpha-driven fishbones appear to be the most threatening instability for fast alpha losses.

2. Nonlinear evolution of alpha-driven Alfvén modes needs careful study.

3. The various alpha-driven modes may appear in near-term devices like CIT.

4. Increased plasma elongation may stabilize some of the alpha-driven MHD modes in regions of nonzero shear.

These problems clearly need much further investigation due to the high uncertainty and importance of these issues.

RIPPLE TRAPPING AND LOSSES

L. M. Hively (ORNL) summarized the present status of modeling toroidal field (TF) ripple loss of fast alphas in tokamak reactors. The resulting alpha losses[4] are low with a peak wall flux of 0.2 MW/m^2 and would have a low impact on the International Tokamak Reactor (INTOR) design. Results by Hitchon and Hastie[5] support Hively's results. Similar calculations by Tani et al.[6] yield losses that are higher by four- to sevenfold, which would have a moderate impact on the INTOR design. The results of Hively and Hastie and of Tani et al. are markedly different in the wall flux distribution and the energy spectrum of lost alphas. Recent Soviet work[7] supports Tani et al.'s result, but is of questionable value because the small banana-width approximation was used for both the orbits and the stochastic ripple diffusion model. More recent calculations by Tani et al.[8] have reproduced the original result, but may not be valid because their mapping procedure was not area preserving. Tani is planning to visit Hively in an effort to resolve the differences in the calculations. New aspects that need to be modeled include the effects of gyromotion, electric fields, and sawteeth.

R. B. White [Princeton Plasma Physics Laboratory (PPPL)] has obtained very recent results via a Hamiltonian guiding center, Monte Carlo calculation, confirming Hively's work. Losses are peaked between the TF coils on the outboard side of the tokamak, also in agreement with Hively. The largest loss contribution comes from the collisionless stochastic regime, which has a sharp Chirikov onset at an interior ripple value of 0.1% corresponding to an edge ripple of ~1%. Recent CIT results confirm this tendency; losses decrease abruptly when the edge ripple is reduced from 2 to 1.3%.

E. Bittoni and M. Haegi [European Nuclear Energy Agency (ENEA), Italy] have used their two-dimensional Monte Carlo, guiding center code to confirm that fusion product confinement in the Frascati Tokamak is neoclassical within the experimental error (50%). They are preparing their three-dimensional code to calculate the TF ripple loss of alphas in INTOR, as a benchmark case, for comparison to the results described above.

Subsequent discussion among the experts brought out the following points:

1. A time scale enhancement of collisional processes relative to the alpha bounce motion to speed up the computations is incorrect for banana orbits.

2. Losses can be scaled via the stochastic ripple diffusion criterion.[9] Ferromagnetic inserts can be used to reduce the TF ripple if necessary.

3. Ripple detrapping cannot be neglected.

4. Care is needed in converting magnetic-field-line coordinates to real space.

5. The wall should be modeled as a constant in minor radius for a circular INTOR plasma, rather than as a constant outermost flux surface, which will be spatially rippled.

6. Benchmark calculations are needed, including the spatial distribution of the wall flux and the corresponding energy distribution of the lost alphas.

7. While ripple losses add uncertainty to ETR performance, the plasma energy confinement time and the critical beta are far more critical.

8. Near-term experiments are needed, e.g., on TFTR, with more detectors. A high-energy, diagnostic neutral beam experiment could test ripple loss mechanisms as well as classical slowing down.

While the basic physics seems well understood, the simulation models need careful comparison. Both the uncertainty and importance of alpha ripple loss are moderate.

ALPHA ASH TRANSPORT AND CONTROL

S. Hu and G. H. Miley (University of Illinois) have studied the effect of alpha ash accumulation on ETR plasma performance in collaboration with N. A. Uckan (ORNL). Ash accumulation in TIBER-II can close the operating window in density-temperature space after 5 to 21 s as the ratio of the alpha-particle confinement time to the deuterium-tritium (D-T) particle confinement time decreases from 35 to 10. Ash removal is definitely needed. Coppi's alpha-fishbone loss mechanism at 400 keV would be nearly ideal for this purpose because alphas are 90% thermalized at this energy. A complete neoclassical theory does not exist for this impurity ($Z = 2$) including large banana-width orbits and pitch-angle scattering on the bulk ions. The uncertain anomalous electron particle flux should be kept in the ambipolar flux balance equation, $\Gamma_e = \sum_j Z_j \Gamma_j$ (where the sum over j includes all ion species). Above $T_e = 15$ keV, the fraction of alphas is no longer very small, i.e., $Z_\alpha^2 n_\alpha / n_i > (m_e/m_{DT})^{1/2}$, requiring a complete treatment of the ions, electrons, and alphas.

J. Mandrekas and coworkers (Georgia Institute of Technology) applied the Stacey-Sigmar impurity flow reversal theory[10] to parallel neutral beam injection in TIBER-II. Depending on the alpha density, a beam power of 25 to 50 MW at 500 keV (also used for current drive) would suffice to expel the alpha ash from the inner 40% of the plasma radius; outside that radius the impurity flux would be inward. A second method for alpha expulsion is ECRH, tailored to produce a plasma potential ϕ, which satisfies $\phi_c/\phi_0 > r/R_0$, with the potential written as $\phi(r,\theta) = \phi_0(r) + \phi_c \cos\theta + \phi_s \sin\theta + \ldots$. The amount of ECRH power to produce such a potential has not been determined yet.

D. E. Post (PPPL) discussed edge alpha pumping by a poloidal divertor and a pumped limiter; high recycling is more difficult to produce with the latter. High heat flux on the pumped limiter would produce a large erosion rate, i.e., hundreds of centimetres per year. Scientists at Argonne National Laboratory have proposed alpha ash pumping via helium implantation arrangements inside the divertor, strongly reducing the pumping requirements.

The subsequent discussion among the experts is summarized as follows:

1. A complete theory (and corresponding experiments) is needed for large banana-width neoclassical alpha transport because the accumulation (or loss) of alpha ash in the core is unclear.

2. If thermal alphas do accumulate in the core, then alpha ash control must be addressed in ETR. The key issue is ash removal from the plasma core. However, ash removal will occur passively during sawtoothing and due to η_i mode transport.

3. Neutral-beam-driven impurity control is expensive; so is enhanced ripple transport. Controlled sawtoothing is a possibility.

4. New, innovative ideas are needed. For example, recent work by Riyopoulos et al.[11] on ion cyclotron resonance frequency-induced turbulent transport could be useful for ash control. Other frequency regimes might be more suitable.

Both the importance and uncertainty of ash control is high.

BURN CONTROL

G. T. Sager (University of Illinois) reviewed the field, including a lengthy bibliography. So far only scoping studies of various methods exist, which do not permit quantitative conclusions. A balance between the physics and engineering requirements has not been found yet. The principal difficulty lies in the transport modeling uncertainties; burn control requirements are a strong function of these uncertainties. For example, one sensitive parameter is low-Q versus high-Q operation of the burning plasma. TIBER is thermally stable for $Q = 5$, but shows great sensitivity to control by lower hybrid current drive at $Q = 750$. A practical and very difficult problem is the accuracy needed for sensing temperature excursions and the response of the burn control system. Excursions of >10% can be diagnosed, but are already dangerously large and hard to control. Burn control is an important element of any long-pulse ignition reactor, but so far concrete, quantitative results are lacking.

R. Potok and coworkers (MIT) have studied active burn control. An optimal operating point is difficult to find in density-temperature space because the temperature dependence of many transport models is weak above 15 keV. Moreover, the neoclassical ion thermal diffusivity is proportional to $T_i^{-1/2}$ and would be thermally unstable by itself. However, the temperature gradient (η_i) mode has a strong, positive T_i dependence and might provide excellent thermal stability. Various external types of thermal control were discussed. Ideal control would have an inherently stabilizing effect without any need for external measures (e.g., a soft-beta limit or an η_i mode). Lacking that, a fusion reactor could be operated in the subignited mode, using controlled auxiliary heating to sustain an even burn.

The subsequent discussion by the panel of experts is summarized below.

1. Active control requires detection of the thermal excursion, an appropriate control system response, and a mode of plasma operation (e.g., subignited) that makes the burn amenable to control.

2. Active burn control candidates include variable input power into a subignited plasma, hydrogen or impurity injection, fueling, compression-decompression, operation at soft-beta limit, and variable TF ripple. While current drive techniques could not change the plasma current fast enough (over an L/R time), the current profile might be modified with sufficient speed to induce instability-driven turbulent transport. INTOR studies[12] have investigated some alternatives, but cannot draw definite conclusions due to uncertainties in the tokamak energy confinement scaling.

3. Passive burn control requires an energy loss channel that depends strongly on temperature. Possibilities include η_i mode losses, synchrotron radiation (requiring operation at a large value of toroidal field), alpha ash accumulation, or operation at an inherently stable burn point.

4. Combinations of these alternatives are also possible.

5. Thermal runaway would increase the neutron yield (a safety problem), would increase the heat flux to the divertor/wall (possible damage), may induce a major disruption (possible reactor damage), and would make the reactor unsuitable for stable power production.

The uncertainty in burn control is high, as is its importance for maintaining a stable, power-producing reactor.

ALPHA PHYSICS DATA BASE AND ETR DESIGN IMPLICATIONS

The final session reviewed the existing understanding for near-term devices. K. M. Young (PPPL) discussed plans for alpha diagnostics in TFTR and CIT. D. E. Baldwin (LLNL) described the recent review by the Magnetic Fusion Advisory Committee (MFAC) of proposed TFTR D-T operation and corresponding alpha physics experimental proposals. D. E. Post (PPPL) and N. A. Uckan (ORNL) presented interesting parameter surveys for CIT and INTOR. The vast amount of INTOR results accumulated over the last decade (e.g., Ref. 12) should be exploited as much as possible for ongoing TIBER/ITER design work.

CONCLUSIONS

Recommendations arising from this workshop are as follows:

1. Control of plasma profiles (density, temperature, current density) has become the key issue in establishing and maintaining a stable, well-controlled burning plasma. More effort in this area is needed.

2. Alpha instabilities may severely constrain the ETR operating space, requiring major modifications to the design. Some instabilities may be beneficial, e.g., the Coppi mechanism for expulsion of nearly thermal alphas for ash control. The present level of effort in this area seems adequate.

3. The TF ripple loss of alphas could have a moderate impact on ETR. The discrepancy between results by Tani et al. and Hively should be resolved as speedily as possible; careful benchmark calculations are needed. A little more effort in this area is needed.

4. The need for alpha ash control is unclear. A complete neoclassical theory for fast alphas is needed. If ash control is needed, simple and inexpensive active techniques will be necessary if adequate passive controls do not exist. A continuing low-level effort is needed here.

5. The need for burn control is also uncertain. Work on an inherently stable burn point is inadequate; tailoring of plasma profiles may help provide such a stable operating point. Passive and active control should be further studied, but are very sensitive to the background plasma confinement. A continuing low-level effort is appropriate.

6. The above theory needs should motivate and be guided by timely experiments on TFTR, Joint European Torus, CIT, Ignitor, and similar devices. Official collaboration exists between the Ignitor and CIT teams with periodic meetings under the auspices of DOE and ENEA, Italy. However, more international collaboration is clearly needed. Table I summarizes the workshop findings for each alpha physics issue in terms of criticality, urgency, and uncertainty.

List of Attendees

U.S. Department of Energy
- R. Dowling

University of Illinois
- G. Miley
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- N. Uckan
- L. Hively
- D. Spong
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ACKNOWLEDGMENT

This work was sponsored in part by the Office of Fusion Energy, DOE, under contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

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