Fusion Theory: Issues, Challenges, Plans

Presented on behalf of the
Theory Coordinating Committee

by J. W. Van Dam

DOE/OFES Budget Planning Meeting
Gaithersburg, MD, March 12 & 13, 2002

Impetus for TCC White Papers on Theory Issues

- FESAC Theory Panel Report (2001) recommended: *"The Theory Coordinating Committee could…call to the attention of OFES, FESAC, and the theory/computing community overarching issues that require timely resolution."*
- In response, TCC determined to set up small subcommittees that would prepare short white papers on theory needs and opportunities in the major topical areas of plasma/fusion research.

Description of Theory Coordinating Committee

- TCC was organized in 1988 by Dave Baldwin. Richard Hazeltine succeeded him as chair in 1991. Since 2000, Vincent Chan has been the chair.
- TCC holds meetings twice a year, in conjunction with the Sherwood Theory Conference and the APS/DPP Meeting.
- The participants in TCC are theory group heads and other leading fusion theorists. Theory program managers from OFES attend the TCC meetings.
- TCC has written letters to program leaders and policy makers, offering information and advice. It also issued three reports.
- Motivated by the FESAC Theory Panel report, TCC is currently producing several White Papers on fusion theory issues, challenges, and plans.

Current TCC Participants

Allen Boozer	Columbia University
Alan Glasser	Los Alamos National Laboratory
Don Batchelor	Oak Ridge National Laboratory
Jim Callen	University of Wisconsin
Peter Catto	Massachusetts Institute of Technology
Vincent Chan	General Atomics
Ron Cohen	Lawrence Livermore National Laboratory
Jim Drake	University of Maryland
Jeff Freidberg	Massachusetts Institute of Technology
Alex Friedman	Heavy Ion Fusion Virtual Natl Lab/LBNL
Steve Jardin	Princeton Plasma Physics Laboratory
Arnold Kritz	Lehigh University
Bill Kruer	Lawrence Livermore National Laboratory
Hank Strauss	New York University
Bill Tang	Princeton Plasma Physics Laboratory
Jim Van Dam	University of Texas
Ron Waltz	General Atomics

TCC Statement of Purpose

The purpose of the Theory Coordinating Committee is to bring to the US controlled fusion program the best insights and results of theoretical physics. To this end the committee attempts to ***identify*** *fusion physics issues that would particularly benefit from theoretical study, and to* ***inform*** *the theoretical community about them. It also* ***investigates*** *administrative developments that might affect theoretical fusion research. Finally, when the committee concludes that fusion program policy could take better advantage of theoretical effort and talent, it attempts to* ***influence*** *that policy.*

(adopted 1993)

TCC: What it is, and what it isn,t

- Scientific theory leadership = doing creative, original research and pointing the way for further development.
- Scientific theory management = making decisions that control what others do.
- Scientific theory coordination = Identify, Inform, Investigate, Influence.

In the past the theory program has been subject to comparatively little management, with the philosophy of clearing the path for scientific leadership by whomever has an original, creative idea. I think most of us approve of this approach of maximizing freedom for theorists to focus on the work that the individual researcher feels is the most effective use of his abilities. It can work for theory much better than for other elements of the fusion program because resources are mostly intellectual rather than hardware, but of course large codes require many of the same considerations as hardware.

— D. Batchelor (Feb 2002)

TCC Letters

Letter to Dr. N. Anne Davies, Associate Director, DOE Office of Fusion Energy Sciences (March 31, 1998).
Letter to Dr. N. Anne Davies, Associate Director, DOE Office of Fusion Energy Sciences (November 23, 1998).
Letter to Dr. Will Happer, Director, DOE Office of Science (November 1997).
Letter to Dr. N. Anne Davies, Associate Director, DOE Office of Fusion Energy Sciences (May 1997).
Letter to Dr. N. Anne Davies, Associate Director, DOE Office of Fusion Energy Sciences (August 14, 1996).
Letter to Dr. N. Anne Davies, Associate Director, DOE Office of Fusion Energy Sciences (March 25, 1996).
Letter to the Honorable J. Bennett Johnston, U.S. Senate (April 89, 1993).
Letter to Professor Robert W. Conn, Chairman, Fusion Energy Advisory Committee (April 24, 1992).
Letter to Dr. Steve O. Dean, President, Fusion Power Associates (April 24, 1992).

TCC Reports

- ***Recent Advances in US Fusion Theory**,* TCC Report #3 (March 1999), 23 pages, authored by D. B. Batchelor, A. H. Boozer, J. D. Callen, P. Catto, V. S. Chan, R. H. Cohen, J. Drake, J. Freidberg, A. H. Glasser, R. D. Hazeltine, and W. Tang.
- ***Opportunities for MFE Theory***, TCC Report #2 (April 1992), 5 pages, authored by D. C. Barnes, A. H. Boozer, V. S. Chan, R. H. Cohen, R. A. Dory, R. D. Hazeltine, G. J. Morales, D. J. Sigmar, and R. B. White.
- ***Opportunities for MFE Theory***, TCC Report #1 (May 1991), 6 pages, authored by D. E. Baldwin, D. C. Barnes, A. H. Boozer, V. S. Chan, R. H. Cohen, R. A. Dory, G. J. Morales, D. J. Sigmar, and R. B. White.

Agendas for Recent TCC Meetings

October 29, 2001

1. Discussion of Response to FESAC theory panel report
   — Plan to write reports about high priority needs and key opportunities in theory
   — Identify TCC members to serve on sub-committees
2. Future Sherwood meetings
   — Suggestions for improvement; should Sherwood join APS Washington meeting?

April 2, 2001

1. Report on SciDAC, FWP, and FESAC theory review status (S. Eckstrand)
2. Discussion on NRC's recommendation regarding establishment of centers of excellence
3. Discussion on the National Transport Code activity (S. Jardin)

October 23, 2000

1. Discussion of theory grant peer-review process—concerns & suggested improvements
2. FESAC review of the theory program — how should theory community prepare for it?

New TCC White Papers

Will be available at TCC web site: http://web.gat.com/theory/tcc/tcc.html.
(currently being iterated upon and finalized.)

- ***Theory Opportunities for Advanced Tokamaks***
- ***Theory Opportunities for Reversed Field Pinches*** [1]
- ***Theory Opportunities for Stellarators*** [2]
- ***Theory Opportunities for Spherical Tori*** [3]

NOTES:

[1] Based on *Outstanding Theoretical Issues for Reversed Field Pinch Research*, summary report from RFP Theory Workshop (January 2000).

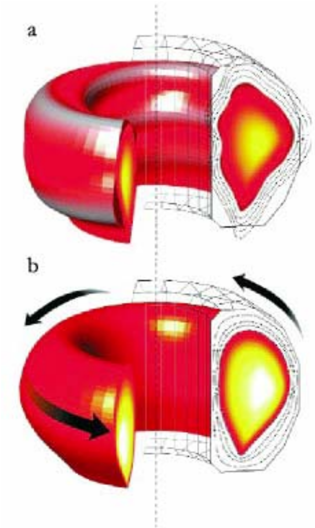
[2] Based on summary report from 3D Theory Workshop (January 2002).

[3] Based on *Spherical Tokamak Theory Development Panel Report* (February 2002).

Advanced Tokamak: Some Highlights

Improved understanding of resistive ballooning modes.

Theoretical ideas of rotation and feedback used to achieve beta greatly exceeding no-wall limit. *Physics Today* (Sept. 2001)



Exptally achieved profiles and f_{BS} identical to theory optimized ones.

Improved understanding of neoclassical effects (BS current) on tearing modes.

Success of reduced models to predict transport in L- and H-mode plasmas, with and without internal transport barriers.

Greatly improved theory and simulations of ITG turbulent heat flux.

Interpretation of “blobs” (field-aligned, radially propagating structures) as large-amplitude interchange instabilities.

Advanced Tokamak: Theory Challenges

1. Steady-state profile control
- — Optimize bootstrap current fraction and beta with wall stabilization (active feedback) and plasma rotation
- — Check consistency of optimized profiles with ideal MHD stability and transport (for auxiliary heating or fusion self-heating)

2. Extended MHD stability
- — Calculate resistive wall mode stability with feedback and rotation
- — Understand onset and interaction of neoclassical tearing modes
- — Evaluate ELM stability and impact on pedestal formation

3. Core transport modeling
- — Include ETG physics to explain momentum and particle transport
- — Include shaped magnetic geometry for e.m. ballooning threshold & Shafranov shift
- — Model intermittency and large-scale events in transport
- — Integrate equilibrium, stability, transport, heating, & boundary physics consistently

4. Edge and pedestal modeling
- — Investigate interplay of MHD and barrier formation
- — Include X-point effects and neutral particle effects
- — Develop long mfp fluid models and fully kinetic edge codes
- — Work toward overlap of core and edge (pedestal, SOL) modeling capabilities

Reversed Field Pinch: Theory Challenges

1. Nonlinear MHD dynamics
2. Resistive wall instabilities
3. Two-fluid effects
4. Profile and shape optimization
5. Pressure gradient effects
6. Kinetic effects
7. MHD computation at high Lundquist number
8. Short-scale turbulence
9. Comprehensive dynamo theory
10. Self-similarity and avalanches
11. Turbulent transport
12. Ohmic, quiescent, sustained plasmas
13. Edge plasma modeling
14. Role of shear flow in confinement

"The understanding and control of transport are arguably the most important scientific challenges within RFP physics…There is a substantial set of challenging topics, as well as a group of committed theorists and computationalists. However, it is evident that the magnitude of the challenge exceeds the quantity of physicists presently at work on the problems."

— RFP Theory Workshop Rpt

Spherical Torus: Theory Challenges

1. Macroscopic stability

— Explain scaling of non wall-stabilized optimized ideal MHD beta limit
— Study role of current-driven modes on beta limit
— Analyze behavior of resistive wall modes with strong toroidal coupling & large flows
— Investigate internal reconnection events; and relation of ELMs and H-mode.
— Extend conventional stability (global kinks, sawteeth, NTMs, FLR/orbit effects)

2. Microscopic turbulence and transport

— Explain large electron energy losses
— Understand nature of turbulence at high beta (→ 1) and low collisionality

3. Fast particle physics

— Calculate ripple losses of NBI ions and alphas at large FLR and low aspect ratio
— Study nonlinear collective instabilities (e.g., compressional Alfvén modes) for large toroidicity and low magnetic field (I.e., beam ion velocity > Alfvén velocity)

4. RF heating and current drive

— Extend RF models (because standard tokamak approximations are invalid)
— Predict RF heating and current drive profiles for non-inductive start-up
— Understand the underlying physics of coaxial helicity injection

Spherical Torus: Theory Challenges–cont.

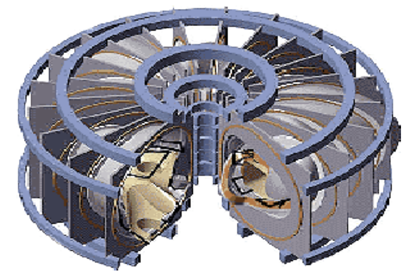
5. **Edge/Divertor**
   — Understand global power and particle accounting
   — Extend theoretical models to low collisionality and large gyroradius
   — Consider liquid metal walls/divertor surfaces to control recycling and sputtering
6. **Integrated system**
   — Analyze techniques for non-inductive start-up and sustainment (CHI, RF, NBI, BS)

"The overarching ST issue is non-inductive current drive in low aspect ratio plasmas.
"The present level of involvement of theorists in ST research is definitely subcritical, for facilitating optimum development of both NSTX and other ST exptal programs.
"Some possible approaches for increasing involvement of theorists in ST research…

- *Support and strengthen…leadership for needed ST theory developments…*
- *Concentrate…physics analysis efforts on a few timely issues…*
- *Produce timely white paper on ST theory issues, and highlight key areas where new ideas could significantly advance ST concept…*
- *Discuss ST issues in terms of the deep underlying physics issues…."*

— Spherical Tokamak Theory Development Panel Report

Stellarator: Theory Challenges



1. MHD: near-term

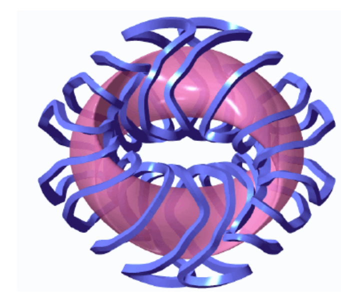
— Understand singular parallel currents

— Accelerate computational models that include island formation

MHD: longer term

— Calculate plasma evolution on resistive & transport time scales

2. Confinement: near-term



— Calculate ambipolar potential, momentum conservation, in-surface flows, bootstrap current, effects of impurities

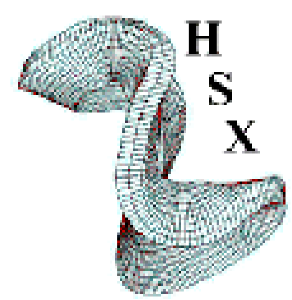
Confinement : intermediate term

— Extend fluid-based models of rotation, flow, & transport to 3D

Confinement : longer term

— Understand microstability and anomalous transport

3. Modeling and diagnostics: near-term

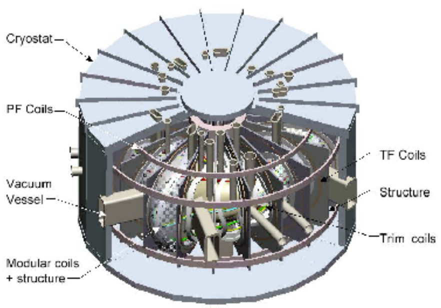


— Develop code for equilibrium reconstruction from exptal data for non-axisymmetric configurations

Modeling and diagnostics: longer term

— Develop predictive transport code for 3D systems

Stellarator: Theory Challenges–cont.



4. Wave propagation & RF: near-term

— Understand validity of approximations to conductivity in 3D
— Accelerate wave solver codes

Wave propagation & RF : longer term

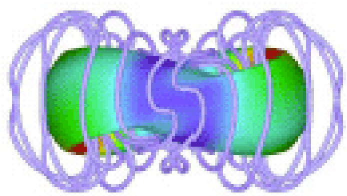
— Determine plasma evolution from Fokker-Planck equation

5. Optimization: near-term

— Complete design of NCSX and QPS devices

Optimization : longer term

— Include surface quality in the optimization process
— Design attractive compact stellarator reactor configuration

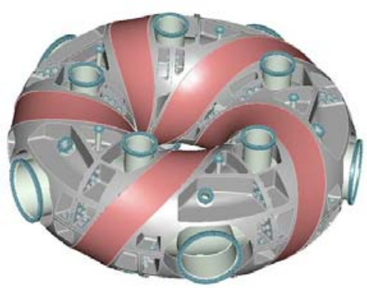


6. Edge physics: near-term

— Implement 3D self-consistent coupled plasma-neutral codes

Edge physics : longer term

— Couple plasma turbulence and edge plasma models
— Develop model for pellet ablation dynamics



“Scorecard” for Theory Coverage

CONCEPT	COMMENT
Advanced Tokamak	Adequate at best
Reversed Field Pinch	Woefully inadequate (for ICCs in general)
Stellarator	Inadequate
Spherical Torus	“Subcritical”

Possible Candidates for Future TCC White Papers

My suggestions:

- Code development and computing initiatives
- Theory developments in basic plasma physics
- Applications and outreach to other science areas
- Burning plasma physics theory
- Theory of budget planning meetings
- Etc.