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Compact Toroid Theory Planning Workshop

*A Panel Report to the Director,
Division of Applied Plasma Physics,
Office of Fusion Energy*

July 1980

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U.S. Department of Energy
Office of Fusion Energy
Division of Applied Plasma Physics

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U.S. Department of Energy
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Division of Applied Plasma Physics
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COMPACT TOROID THEORY PLANNING WORKSHOP

A PANEL REPORT TO THE DIRECTOR, DIVISION OF APPLIED PLASMA PHYSICS,
OFFICE OF FUSION ENERGY

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I. Introduction

A Compact Toroid Theory Planning Workshop was held on Wednesday and Thursday, May 28 and 29, 1980, at Department of Energy Headquarters in Germantown, Maryland. The Workshop Panel was composed of H. Berk (LLL), R. Gerwin (LASL), W. Grossmann (NYU), J. Johnson (PPPL), A. Kadish, Chairman (SAI), E. Ott (University of Maryland), and L. Steinhauer (MSNW). W. Dove of DOE was present as a consultant to the Panel.

The purpose of the Workshop (see Appendix A) was to identify the most important physics issues that need to be addressed in the near term in order to assure the optimal design and timely interpretation of Compact Toroid (CT) experiments. The Panel was also asked to assess the levels of effort required to obtain priority information on appropriate time scales compatible with DOE plans to design a CT proof-of-principle experiment.

The fiscal year cost anticipated for the effort recommended by the Workshop Panel (excluding costs for computing) is estimated to be approximately \$5.7M. CT theory is currently funded at a level of approximately \$2.0M per year.

II. Summary of the Workshop Panel's Recommendations

For emphasis, the priority problem areas identified by the Panel are grouped into five categories. These categories overlap as a result of the impact that information from any one category would have on the others. The categories chosen were Formation and Equilibrium, Stability, Transport, Heating, and Reactors. The following table identifies the high priority areas within these groupings, together with a summary recommendation of levels of effort.

<u>CATEGORY</u>	<u>MANPOWER/YEAR</u>	<u>NEAR-TERM PRIORITIES</u>
A. Formation & Equilibrium	6	Formation
	4	Translation & Control
	5	Configurations
B. Stability	10	Macrostability
	4	Finite Gyroradius Effects
	6	Microstability & Turbulence
C. Transport	6	Self-Consistent Codes
	6	Modeling of Existing Experiments
	4	Sheath Physics
D. Heating	3	Ohmic Heating
	4	Compressional Heating
	2	Beam Heating
	5	r.f. Heating
E. Reactor	6	Conceptualization

The Panel feels these are the basic areas that need to be addressed and receive sustained attention if the various compact toroid experiments are to be properly designed and interpreted prior to DOE commitment to a CT proof-of-principle experiment in the next four to five years.

The Panel feels that it is appropriate to focus on those areas of compact toroid research which are necessary in order to ensure a timely interpretation of experiments compatible with OFE's target date for the designing of a CT proof-of-principle experiment. The diversity of compact toroid experiments together with their associated device specific physics issues and limitations on

manpower resources make it impractical to make recommendations in every physics area of interest. If the compact toroid program should become less diverse in the near future, the list of priority areas for theoretical research may change. The research areas recommended here will, however, provide a strong theoretical foundation for the CT program in the near future.

II.A. Formation and Equilibrium

The diversity of CT experiments and their associated plasma formation procedures and final equilibrium states raise numerous device specific physics questions. These are in addition to those questions which are generic to the compact toroid program. The various devices are characterized by the method of start-up and the magnetic geometry (the presence or absence of a toroidal magnetic field).

The induction and gun devices generate spheromak plasmas having both toroidal and poloidal magnetic fields. The theta-pinches normally produce purely poloidal fields but by imposing additional axial currents one can also generate toroidal fields. Other experiments feature charged particle rings aimed at generating field reversal followed by plasma injection. Most efforts are concentrating at present on the plasma formation itself. In some cases, translation of the toroid out of the formation chamber will be examined in a future phase. Some of the experiments have built-in flexibility and may be able to access a broad range of plasma configurations (e.g., a range of poloidal fluxes or separatrix radii). By this means some control of the equilibrium will be possible. The pros and cons of each method resides not only in its stability and transport properties, but also in its implications for reactor scaling and heating requirements.

Theoretical studies of plasma formation have not been extensive, although a number of powerful computational tools have been formulated and adapted for compact toroid studies. While some of the physics issues are qualitatively understood, the basic issues require a quantitative treatment if future experiments are to be optimally designed and operated in a timely fashion. The desired conclusive correlations with experiments will not be possible until a more detailed data base becomes available. Spatially-resolved (r,z) temperature and density measurements for a broad range of equilibria are particularly needed to get beyond cursory comparisons between theory and experiment.

Several MHD codes and hybrid codes have been adapted to study plasma formation in existing experimental configurations. Atomic physics packages are available to simulate non-equilibrium ionization and radiation processes during formation. Several equilibrium codes are in use. As a result of the complexity of the formation problem these codes are expensive to run. Modified codes using optimal numerical schemes will be necessary if this problem is to be well understood in the future. The Panel feels that teams of two to three scientists working on plasma formation problems, associated with each given concept, should be adequate. Simple models should be developed to determine the effect of various non-ideal factors (e.g., resistive wall, plasma decay, field-shaping) on the gross features of equilibrium (e.g., separatrix radius, elongation, aspect ratio). Atomic physics effects during plasma formation should be studied with improved packages. Hybrid codes should incorporate finite electron temperature and electron energy transport. Finally, theory and experimental data relevant to reconnection and anomalous resistivity during

formation (particularly the detailed radial density and temperature structures) should be brought to bear on the nature of anomalous transport coefficients used in MHD codes.

Kinetic studies should be undertaken to determine velocity space distributions associated with macroscopic equilibria. These should aid in the assessment of microinstabilities and transport.

The Panel feels that the basic theoretical questions regarding translation are those of control and integrity of the equilibrium. The integrity is really a stability problem. The control of the equilibrium can be studied with fluid codes and with simple modeling.

The MHD theory for 2-D equilibria is well understood and many tools are available for determining relevant configurations. The Panel recommends that studies continue on the properties of 3-D compact toroids equilibrium because of the possibility of using Ioffe bars.

If these recommendations are implemented immediately, substantial progress on formation and equilibrium should be available on time scales compatible with DOE programmatic projections.

III.B. Stability

As with most magnetically confined plasmas, an understanding of stability is essential for compact toroids configurations. Analytic work predicts that some macroscopic instabilities (particularly tilting modes) can be stabilized by shaping the plasma cross section to be oblate and by having perfectly conducting walls close to the plasma. This has contributed significantly to current interest in this approach. These results have also been obtained from

computational models and tilting modes have been seen in experiments. Techniques are available for detailed investigation of various aspects of this problem so that considerable progress can be made by making relatively minor changes in existing stability codes. However, new initiatives are needed to address problems such as those associated with the finite conductivity of the chamber walls, the importance of gyration radius and other particle effects, the nonmaxwellian character of the velocity distribution in many compact toroid embodiments, and the effect of rotation and velocity shears and flows.

The problem of ideal magnetohydrodynamic stability is being addressed analytically and with available tokamak codes including normal mode and 3-D time dependent codes. Modifications are needed in some of these codes to remove restrictions preventing operation with the toroidal field from passing through zero and to allow the axis of symmetry to move or tilt. Considerable effort should be made to understand the effect of shaping the cross section on stability so as to determine how far the walls can be moved from the plasma. In most of the present work the plasma model has incorporated a vacuum in the region of open field lines between the plasma and the wall. A good understanding can and must be obtained concerning the effect of having good conductivity in this region. Since our understanding indicates that the walls must be close to the plasma, it is important to investigate the effect of flux leakage through walls with finite conductivity. Experience with tokamaks has shown that stability is very sensitive to minor changes in shape of the pressure and current distributions so that stability calculations should be made at frequent intervals during the formation phase and evolution of a discharge. Calculation using model geometries to approximate extremely prolate configurations

should be continued. An indication of the sensitivity of the stabilization associated with compressibility in closed line devices, such as those with no toroidal fields, to field errors would be useful. The Panel recommends that approximately ten men/year be spent on microstability studies.

In many compact toroidal configurations the ion gyration radius is comparable to the plasma dimensions or to the width of the region of large pressure gradients. Thus, gyration effects could significantly alter ideal stability predictions as seems to be suggested in current experiments. These effects may be particularly important for systems with no toroidal field and for Astron-like configurations using relativistic electrons or high energy ions to provide field reversal. Some tools, such as particle hybrid codes are available to address these problems but additional development is needed. The Panel estimates that four men/year should be expended on this type of problem.

Many stability studies and techniques developed for other configurations are readily applicable to compact toroids. Examples include the reversed field pinch and tokamak. Similar treatment should be carried over to compact toroids. In particular, the particle streaming associated with plasma currents could excite current-driven drift modes. There exists an abundance of microinstabilities which could be responsible for transport processes, especially near the separatrix surface at the edge of the plasma. It would be useful to study these instabilities and to estimate their contribution to plasma turbulence. The Panel recognizes that techniques have been formulated to study these problems. It estimates that six men/year should be spent in this area.

III.C. Transport

Given the existence of macroscopically stable equilibrium for steady-state or long pulse compact torus operation, transport processes will ultimately determine the economic feasibility of the concept as a reactor. In recent years the basic theory needed for transport codes with self-consistent equilibrium (1 1/2-dimensions) has been developed and such codes are now operational in several research centers. These codes can be used to test understanding of experiments, ascertaining whether theoretically stable configurations are achievable and determining the confinement and fusion burn characteristics of proposed compact toroid reactor configurations. The self-consistent 1 1/2-D transport codes which treat the bulk plasma can now be constructed with complete physics packages which include classical and neo-classical transport coefficients, impurity and atomic physics processes and fusion rate data. The basic classical and atomic coefficients are known, while neo-classical coefficients, though in need of further refinements, can be estimated. These coefficients need to be organized for efficient code utilization.

Further, the codes should include anomalous transport effects to model probable turbulence from plasma instabilities. Here the precise coefficients are speculative so that appropriate coefficients need to be determined empirically as well as from future theoretical calculations. A large effort will be needed in this area to explain both current and future experimental data. Some analysis has been performed using turbulence coefficients associated with the lower hybrid mode, but these models need more study. The Panel believes the several teams of two to three scientists each will be needed to adequately

research this subject area.

The Panel believes that an important area for study and development is the description of the sheath at the plasma edge. Current experimental data and analysis indicate that plasma loss through the sheath may contribute to the build-up of plasma rotation and ultimately lead to instability. If this is the case, control of this effect will clearly be important. As the sheath is also at the interface of open and closed field lines, it may be possible to take advantage of open field confinement by particle mirroring or electrostatic plugging. The physics developed in tokamak divertor studies and mirror confinement should be used here.

Besides conventional transport mechanisms, quantitative models are needed to describe processes that can lead to a steady-state configuration. Several mechanisms have been proposed such as r.f. driven currents, and neutral beam driven currents arising from Ohkawa currents or magnetic pumping in a toroidally rippled field. The transport codes need to be able to incorporate these concepts as well as future ideas.

The Panel believes that complete and realistic transport modeling can be obtained. The initial priority should be to agree with experiment where it is likely that the understanding of anomalous effects is needed. Undoubtedly, simple models will be useful in attaining such understanding. Ultimately, the goal is to achieve a reliably predictive transport package with which reactor systems can be analyzed. Here, too, the Panel believes that several teams of two to three scientists are required to obtain an adequate understanding and capability in the subject area.

III.D. Heating

There are several possibilities for heating compact toroids to ignition such as ohmic, compression, or r.f. heating and charged or neutral beam injection. Also, alpha particle depositions must be considered. To date temperatures of a few hundred eV have been achieved. To obtain higher temperatures auxiliary heating experiments may be necessary.

Inputs from studies under other headings of this report may strongly impact heating. For example, the possible necessity for stability of a closely fitting conducting wall may rule out or make undesirable heating schemes which require large ports or antennae near the plasma. Furthermore, we note that the injection of particle beams and r.f. heating can be used to sustain toroidal currents. The question of such current drivers deserves further study.

The simplest heating concept for compact toroids is ohmic heating. Here, the plasma depletes its initial magnetic fields, resistively converting their energy to thermal energy. For low beta plasmas, large temperature increases are thus achieved without appreciable alteration of the field profiles.

The Panel believes that a team of three people is required to properly study "ohmic heating to ignition." It should develop and use a self-consistent adiabatic toroidal code, with various transport effects, impurity effects, monitoring of stability, and realistic non-local alpha deposition. A fundamental question that should be answered in this study is to what extent it is necessary to externally drive the ohmic heating current in order to reach ignition.

Another heating concept for compact toroids is adiabatic compression. Here, one has a choice of either flux compression or of wall compression (liner concept).

A third scenario consists of axially driving a compact toroid into a converging tube. It has the advantage of combining the translation and heating phases into a single step. Fast compressional heating via axial shocks may also offer an attractive option.

Compressional heating can be studied theoretically by means of existing toroidal codes. The only difference in the application is in the boundary conditions. Two people working in tandem with the three on ohmic heating could properly cover both heating schemes.

Magneto-acoustic heating is a process whereby the plasma acts like a resonant cavity, storing energy until it can be absorbed by some kind of dissipative mechanism. The sharper the resonance line (i.e., the higher the Q and the smaller the dissipation parameter) the more effectively wave energy is dissipated in the plasma when the cavity is driven on resonance. That this heating process works effectively has been demonstrated experimentally in theta pinch plasmas of a wide range of collisionality. Temperatures have been observed to increase significantly in about half a dozen cycles.

A potential advantage of this kind of heating scheme is that it might be made to heat the plasma on a much shorter time scale than some other methods. It could be a useful transiently applied heat source, in the event that ohmic or adiabatic compressive heating cannot quite reach ignition due to anomalous

losses. In view of the demonstrated heating by this means, the Panel believes that a small effort to study this process would be worthwhile. Machinery is currently available in the form of fluid and particle codes and ongoing linear theory so that a reasonable effort could be mounted by a small number of people, say two.

Neutral, as well as charged particle, beams offer another possibility for energy input to compact toroids. In the case of charged particles, transport across magnetic field lines so as to penetrate the plasma remains a fundamental problem. However, for compact toroids it may be possible to inject particles along the open field lines into the closed line region through the field null on the separatrix. The ability to inject in this fashion requires further investigation. Neutral beams, on the other hand, offer a well-proven and understood method that has already met with considerable success. The Panel recommends that two people be involved in beam injection studies.

R.F. heating at the first and second electron cyclotron harmonics requires sufficiently low density for accessibility of the wave to the plasma. Thus heating of high β devices may not be possible with this method. ECRH may be suited to spheromaks if they are produced at low β . Lower hybrid wave heating has been studied extensively for tokamaks, and a good deal of theoretical knowledge exists. However, lower hybrid wave heating has been found to be subject to nonlinear processes whose effects have so far made it difficult to obtain a complete understanding of this heating method. Nevertheless, the ease of production of r.f. in this frequency range may make it an attractive candidate for heating in compact toroids. ICRH has been very successful in tokamak heating and, for this reason, should probably receive a good deal of

attention. Concepts and tools already developed (e.g., ray tracing codes and launching antenna concepts) should be utilized to obtain an initial idea as to the utility of r.f. heating in compact toroid configurations. The Panel recommends that three people be devoted to r.f. heating studies.

The Panel notes that the recommended manpower for heating studies is large in the absence of a firm data base. This was done deliberately because the Panel recognizes that many heating approaches may be viable. Studies are needed now so that informed decisions may be made when sufficiently long confinement is achieved to allow for auxiliary heating.

III.E. Reactor Aspects

The ultimate goal of the compact toroid program is a viable reactor embodiment. The Panel recommends that the level of effort on reactor analyses be increased to six men per year.

The Panel recognizes three basic reactor configurations: (1) the static spheromak with both poloidal and toroidal magnetic field, (2) the static field reversed configuration with only poloidal magnetic field, and (3) the moving ring configuration where the plasmoid may or may not contain a toroidal magnetic field.

There exist at present 0-D and 1-D codes which have already been used and may be of further use in scoping out the global features of a particular reactor configuration. The Panel feels, however, that the special geometrical considerations of compact toroids, e.g., low aspect ratio and separatrix with null field points, require a more realistic simulation code to sharpen the predictions emerging from the reactor studies. The recommendation is that

the 1 1/2-D model transport codes used to simulate and interpret existing experiments be extended to include the requisite reactor modules such as burn dynamics and α -particle treatment. The use of finite orbit Monte-Carlo techniques is particularly relevant here. Such a reactor simulation code could be expected to provide a more detailed comparison of the various compact toroids reactor approaches.

For spheromak and field reversed configuration reactors the relative merits of pulsed and steady-state operation must be determined along with wall loading requirements. The important problem of α -particle confinement in compact toroid fields requires investigation and must be carried out with reference to the possible requirement of walls close to the plasma. Q enhancement of field reversed configurations by the use of multiple cells should be investigated. Refueling scenarios are required and the question of alternate fuel cycles (e.g., Deuterium based fuel cycles) which may benefit from low field strength regions needs to be addressed.

Moving ring configuration reactors should be investigated with reference to the relative merits of charged particle beam formation, drift chamber, adiabatic compression and eventual direct energy conversion. The α -particle confinement and appropriate fuel cycle definition are equally important issues and should be investigated.

The Panel feels that three teams of two scientists is sufficient to carry out the required reactor definition studies. A final recommendation is that the reactor study teams maintain close contact with available theoretical groups and assimilate developing theoretical findings into the systems studies.

ACKNOWLEDGEMENT

The Panel wishes to thank Jim Decker, Director, Division of Applied Plasma Physics, and Dave Nelson, Chief, Fusion Theory and Computer Services Branch, for informative discussions of the status and objectives of the DOE compact torus program. The Panel also wishes to acknowledge the valuable assistance of Bill Dove, Chief, Advanced Fusion Concepts Branch, both in the Panel's discussions and for the materials he prepared for the Panel prior to those discussions, and also the contributions of Bill Condit.

Department of Energy
Washington, D.C. 20545

April 25, 1980

To the Compact Torus Theory Planning Workshop Participants

Dear Colleague:

Thank you for agreeing to participate in the Compact Torus Theory Planning Workshop. The Panel will meet on Wednesday, May 28 and Thursday, May 29, 1980, at the Department of Energy in Germantown, Maryland at the Century XXI complex in room A2-3223. The Workshop will convene at 8:45 a.m. on Wednesday. The Panel will consist of Herb Berk, LLL; Dick Gerwin, LASL; Bill Grossmann, NYU; John Johnson, PPPL; Abe Kadish, SAI, Chairman; Ed Ott, University of Maryland; Marshall Rosenbluth, IAS; and Loren Steinhauer, MSNW. As you know, compact torus research has expanded rapidly in the last two years. The encouraging results obtained from recent experiments suggest further growth of the theory effort in the next few years.

The Fusion Theory and Computer Services Branch of the Office of Fusion Energy has determined that a document which identifies the status and priority needs for near-term theoretical research in compact toroidal configurations would aid in planning this research and in informing researchers interested in contributing to this promising area. The Workshop Panel will be writing the planning document.

The Branch held an EBT Theory Workshop in February 1979 which produced a Panel Report of this type. The report was very well received in the field, continues to be a requested information source today, and serves as a guide in planning future research. I have enclosed a copy in order to provide you with an idea of the kind of end product I have in mind for the Workshop.

I will be in communication with you soon. I look forward to seeing you in May.

Sincerely,

A handwritten signature in dark ink, appearing to read "Dave", is placed above the typed name.

David B. Nelson, Chief
Fusion Theory & Computer
Services Branch
Division of Applied Plasma Physics
Office of Fusion Energy

Enclosure

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