The Status of Compact-Toroid Research Using High Energy Particle Beams

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

MASTER

October 1980

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

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U.S. Department of Energy
Office of Energy Research
Division of Applied Plasma Physics
Washington, D.C. 20545

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PARTICLE BEAM/COMPACT TOROID WORKSHOP

A PANEL REPORT TO THE DIRECTOR FOR APPLIED PLASMA PHYSICS, OFFICE OF FUSION ENERGY, ON THE PB/CT WORKSHOP OF JUNE 26-27, 1980

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Prof. T. Kammash, University of Michigan
Dr. R. K. Linford, LASL
Dr. A. C. Smith, Jr., Pacific Gas and Electric Company

Workshop Members

Prof. H. Fleischmann, Cornell University
Dr. J. Greenly, Cornell University
Dr. C. A. Kapetanakis, NRL
Prof. R. Lovelace, Cornell University
Dr. Scott Robertson, University of California, Irvine
Dr. John Sethian, NRL
Prof. R. N. Sudan, Cornell University

APPROVED BY THE PANEL MEMBERS

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A. C. Smith, Jr.

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Executive Summary

A workshop on the use of high-energy particle beams to generate compact-toroid plasma geometries was held at the Department of Energy (Germantown) on June 26-27, 1980, for the purpose of assisting the Division of Applied Plasma Physics in formulating program plans for this work, and assessing its importance relative to the rest of the compact toroid (CT) program. The scope of the workshop is given in Appendix A, and the charge to the panel of advisors responsible for writing this report is given in Appendix B.

Based on oral and written submissions by several members of the PB/CT community, the panel feels that particle beam work should be continued at the highest level consistent with APP budget planning. The presentations to the panel made three significant points:

- Particle-beam devices may lead to interesting, though not outstanding, compact toroidal fusion reactors in their own right (energy gains of 5-12 appear possible with DT).
- Charged-particle injection techniques offer significant benefits to other compact toroidal devices, particularly in the areas of formation, heating, and instability control, thus
- A combination of the large-orbit particle beam configurations with the existing small-orbit configurations such as the FRC (Field-Reversed Configuration) or the Spheromak appears natural and very attractive.

The first point was discussed at some length in a 1978 DOE report (DOE/ET-0047), and although considerable new work was reported, it does not seem possible to get higher energy gains from a reactor in which the confining current is carried solely by high energy ions. Further conceptual studies on this point are warranted at a low level, but the subject has been extensively studied.

The last two points are the most important. Both early FRC experiments at TRW/STL and Spheromak experiments have been subject to an instability (the "tilting mode"). In several experiments to date, close-fitting conducting walls seem to have been required to stabilize this mode (as in the case of the LASL and LLNL gun-injected Spheromak plasmas; the LASL FRX A/B experiments have not had tilting problems.) Particle-ring techniques have generated CT configurations consistently for several years without observing this instability. Conducting walls were used, but their radii were more than double the ring radii in many cases. The suggestion has naturally come forth that a combination of the large-orbit and small-orbit techniques may result in a stable, high-energy-gain configuration with relaxed restraints on the close fit of the conducting wall. Relaxing these restraints should be important both for many of the CT reactor designs and for interim CT physics experiments. Theoretical studies of this are under way, and partial understanding and confirmation of the above ideas has been obtained from computer simulations.

The above discussion summarizes the panel's findings. Details are given in Table I. In addition, the panel expressed a very high opinion of the quality of the presentations made. The work presented obviously represented the result of years of sustained and carefully planned work by the scientists involved. The panel felt strongly that this group of scientists represents a valuable resource, and that their work should continue to be carefully integrated into the overall compact toroid program.

TABLE 1
PANEL RECOMMENDATIONS
ON FUTURE PB/CT WORK

- DETAILED EXPERIMENTAL DESIGNS ARE NEEDED FOR ATTAINMENT OF FIELD-REVERSED ION RINGS AND CT START-UP.
- IMPROVED ENERGY-GAIN CONCEPTS ARE NEEDED FOR LARGE-ORBIT ION RING REACTORS. ONE IDEA, FOR WHICH A THEORETICAL BASIS HAS BEEN DEVELOPED, IS TO COMBINE THE LARGE-ORBIT AND SMALL-ORBIT CONFIGURATIONS. THIS IDEA SHOULD BE PURSUED DILIGENTLY.
- ELECTRON EXPERIMENTS WILL PROBABLY CONCENTRATE ON TWO MAJOR ISSUES;
 - (1) CT START-UP AND CREATION OF PB/CT COMBINATIONS.
 - (2) STABILITY AND CONFINEMENT STUDIES OF BACKGROUND PLASMA IN CT CONFIGURATIONS.
- ION EXPERIMENTS WILL PROBABLY CONCENTRATE ON THE TECHNOLOGY OF ION BEAM GENERATION, FIELD-REVERSED RING FORMATION, AND RING TRAPPING.
- PARTICLE BEAM TECHNIQUES ARE POTENTIALLY USEFUL TO SMALL-ORBIT CT'S IN SEVERAL WAYS, INCLUDING FORMATION, EQUILIBRIUM SHAPING, STABILITY, HEATING, REFUELING, AND RE-FLUXING.

II. Introduction

There are several closed-field magnetic confinement schemes which offer the possibility of making small or medium-sized fusion reactors with moderate applied fields of 20-100 kG. The concept with the longest continuous history of experimental and theoretical development is the particle-ring approach, in which the confining magnetic field is provided by a high-current ring of very energetic charged particles orbiting in a relatively uniform external magnetic field with weak magnetic mirrors or field shaping to center the plasma. The ring current is sufficiently strong to locally reverse the direction of the external magnetic field ("field-reversal"), giving rise to the pattern of closed magnetic field lines shown in figure 1. DT background plasma will be confined on these field lines. This configuration was studied experimentally in the Astron program at LLNL and is under study in the RECE experiments ("Relativistic Electron Coil Experiments") at Cornell University. Both of these programs have used medium or high-current particle beam accelerators to generate the particle rings.

Similar magnetic field configurations can be formed by causing the applied field in a theta pinch to change polarity rapidly (field-reversed theta pinch), or by causing plasma to flow into the confinement region with the proper fields embedded in it (Spheromak and Coaxial-Injector approaches). These schemes generally rely on low and medium-energy particles to carry the plasma current which generates the confining magnetic field. The particles have orbits small compared to the plasma ring dimensions. Generally, configurations similar to that in figure 1 are called "Compact Toroids," abbreviated as "CT". The configuration may have an embedded toroidal magnetic field in addition to the poloidal fields in figure 1, in which case it is called a Spheromak, or it may be a purely field-reversed poloidal field configuration (FRC). To the extent that CT's are stable and long-lived, it is expected that they will have favorable plasma confinement properties, due to the closure of the magnetic field lines, irrespective of whether the current is carried by particles with large orbits or small orbits. The different compact toroid schemes differ mainly in their ease of formation, macro- and micro-instability characteristics, and potential for making viable fusion reactors.

Since there are a large number of approaches to CT generation, several conferences and workshops have been held, most recently at PPPL in December, 1979, to report research results. The present meeting was called by OFE/APP specifically to evaluate the high-energy particle beam approaches in relation to the rest of the CT program, to help integrate the PB/CT program planning into the overall CT program plan, and to stimulate the workers in the field to cover topics of importance to the fusion development program. A panel of advisors with backgrounds in PB/CT work was assembled to do the evaluation, and presentations were made by representatives of the major contractors in the field.

A major portion of the workshop time was spent in documenting the status of PB/CT work to date. The highlights of this work are given in Table II. Briefly, field-reversed particle-ring CT's of significant strength ($\Delta B/B = 2$) and lifetime (over a millisecond) have been generated using electron beam injection. They appear to be useful configurations for plasma confinement experiments. The panel noted that, although plasma confinement measurements have not been performed in these experiments, there have been experimental reasons why this has not happened (auxiliary heating has not been available), and there are well-developed plans to carry out these measurements in FY 81-82 if the electron experiments are continued at the present level of effort. Pure electron-ring configurations cannot be used in a fusion reactor since synchrotron radiation losses exceed the fusion power produced. Thus attempts to form CT configurations by ion beam injection into appropriate magnetic fields have been begun, and have produced initial successes, together with a good base of technological capability and the tools for theoretical understanding. Also, rotating electron beams have been used to create CT configurations by inducing appropriate plasma currents in initially non-ionized gases, which gives a third possible mode for PB/CT plasma initiation.

TABLE II:
HIGHLIGHTS OF ACCOMPLISHMENTS
TO DATE

- FIELD-REVERSED ELECTRON RINGS WITH $\Delta B/B_0 = 1.9-2$ HAVE BEEN OBTAINED. FIELD DECAY AND RING PARTICLE ENERGY DECAY IS IN GENERAL CLASSICAL (LIFETIMES IN THE MILLISECOND RANGE HAVE BEEN OBSERVED.) PLASMA TEMPERATURES HAVE BEEN KEPT LOW BY LACK OF AUXILIARY HEATING.
- TRANSIENT FIELD REVERSAL HAS BEEN ATTAINED BY ION INJECTION. FIELD-REVERSED ION RINGS HAVE NOT BEEN TRAPPED -- THEY HAVE A LARGE RATIO OF AXIAL TO PERPENDICULAR ENERGY IN THE PRESENT FIELD-REVERSED ION INJECTION EXPERIMENTS.
- CAREFULLY-DESIGNED ION INJECTORS WITH A LOW SPREAD IN ANGULAR MOMENTUM HAVE PRODUCED WEAK ($\Delta B/B_0 \sim 0.08$) ION RINGS IN WHICH THE SELF FIELD IS IN EQUILIBRIUM WITH THE AXIAL PRESSURE. THESE RINGS HAVE BEEN PROPAGATED AND REFLECTED FROM MAGNETIC MIRRORS.
- SELF-CONSISTENT RING-PLASMA EQUILIBRIA HAVE BEEN COMPUTED WITH FIELD REVERSAL $\Delta B/B_0 = 1.8$ AND PLASMA $\beta = .4$. THE STABILITY OF THESE EQUILIBRIA IS BEING EVALUATED. THESE CONFIGURATIONS ARE A HYBRID BETWEEN PURE PARTICLE RING CONFIGURATIONS AND SMALL ORBIT CT'S.
- THE GROSS PRECESSIONAL STABILITY THEORY AND TILTING (KINK) STABILITY THEORY OF PARTICLE RINGS HAS BEEN ANALYZED, AND HAS BEEN PARTIALLY VERIFIED BY COMPUTER SIMULATIONS. THE THEORY, LARGELY VERIFIED BY THE ELECTRON-RING EXPERIMENTS, GIVES CONFIDENCE THAT USEFUL PLASMA CONFINEMENT CONFIGURATIONS CAN BE MADE.
- CONTROLLED MOVEMENT OF RINGS IN THE PRESENCE OF RESISTIVE WALLS AND RESISTIVE PLASMA HAVE BEEN STUDIED THEORETICALLY AND EXPERIMENTALLY. THE AGREEMENT BETWEEN THEORY AND EXPERIMENT IS VERY GOOD.
- IN PREVIOUS WORK, REACTOR ENERGY GAINS OF 2-3 WERE PREDICTED. NEW IDEAS FOR ION RING REACTORS WERE PRESENTED WHICH SUGGEST THAT, USING DT BURN, PLASMA ENERGY GAINS OF $Q = 5-12$ MAY BE ATTAINABLE FOR A PURE ION RING REACTOR. THESE ARE:
 - (A) CONSIDERATION OF THE EFFECTS OF INDUCTIVE ELECTRIC FIELDS ON RING LIFETIME.
 - (B) UTILIZATION OF A LARGE RATIO OF PLASMA TO RING VOLUME.
 - (C) CONSIDERATION OF THE DETAILED EFFECT OF NUCLEAR SCATTERING ON RING LIFETIME.
 - (D) EFFECTS HAVING TO DO WITH RING AND PLASMA PROFILES.

TABLE II: (CONTINUED)

- STUDIES INDICATE THAT EVEN HIGHER VALUES OF Q MAY BE OBTAINED BY THE HYBRID PARTICLE RING - SPHEROMAK OR PARTICLE RING - FRC CONFIGURATIONS.
- THE PARTICLE RING CONFIGURATIONS OFFER A POSSIBLE METHOD FOR CLEAN COMPACT TOROID GENERATION. SINCE THE ORIGINAL FORMATION OF THE CT CONFIGURATION TAKES PLACE VERY RAPIDLY, AND AT SOME DISTANCE FROM SOLID WALLS, IMPURITY GENERATION SHOULD BE STRAIGHTFORWARD TO CONTROL.
- CROSS-FIELD PROPAGATION OF POLARIZED ION-ELECTRON ("I-E") BEAMS IS UNDER STUDY AS A GENERAL METHOD OF HEATING FUSION DEVICES.
- CONCEPTUAL STUDIES OF MERGING PARTICLE RINGS WITH EXISTING CT PLASMAS HAVE BEGUN. GENERAL THEORETICAL ARGUMENTS SUGGEST THAT ADDITION OF A PARTICLE RING TO AN EXISTING CT MAY PROVIDE USEFUL HEATING AND STABILIZATION OF THE CT.

Workers from the major ion-ring programs involved (Cornell, NRL) have collaborated on a study of a pure ion-ring reactor, which was first presented in a 1978 D.O.E. report (DOE/ET-0047, "An Evaluation of Alternate Magnetic Fusion Concepts"). This study was done carefully, and resulted in what the panel feels was a good initial evaluation of a pure ion-ring approach. As mentioned in Table II, possible plasma energy gains for DT burn are now thought to be in the range of $Q=5-12$, assuming good plasma confinement and conservative ion-ring generation and configuration parameters. This is an interesting value of Q , but one which does not leave much margin for unforeseen difficulties. Fortunately, the theoretical work points out that the development of finite background plasma pressure in the ion ring configuration will cause more of the current to be carried by the background ions and electrons, a result already anticipated in the Astron work, thus reducing the energy losses associated with the high energy ions, and increasing the Q . Since much of the current is now carried by particles with small orbit size, this transfer of current represents a hybridization of the particle-ring approach with the small-orbit CT approach. The panel and the workshop participants were unanimous in their feeling that this hybridization needs to be vigorously studied. There was remaining debate as to whether the particle-beam approaches would be best combined with FRC's or with Spheromak's. The panel feels that this question will be resolved by continuing systems studies and theoretical work, as well as by developments in the Spheromak and FRC programs. Several of the presentations pointed out that the inclusion of high energy particles should enhance the stability of Spheromaks and FRC's, and hence that the hybrid configurations offer possible advantages with respect to simple small-orbit CT's. The panel agrees with this conclusion, and notes that computer codes have been developed to address this question quantitatively.

As directed, the workshop addressed the question of benefits of the particle-beam work to the rest of the CT program. As indicated in Table I, there are several possible benefits in addition to the formation of hybrid configurations described above. Presentations were made showing that particle beam methods should be useful in the start-up and heating of Spheromak's and FRC's. The panel noted that theoretical, and computational tools have been or are being developed to evaluate carefully these ideas, and feels that future experimental programs should be given the resources to utilize these tools to fully analyze the data, and then to evaluate proposed CT start-up and heating experiments. It was also noted that particle-ring confinement studies will contribute to the basic understanding of confinement for all CT's.

The panel felt that it was inappropriate to make general recommendations on resource requirements, and particularly on funding levels, in view of the limited time available. There was not much material presented to allow an assessment of the consequences of different levels of effort. The contractor presentations, with one or two exceptions, did not respond in depth to question #3 of the scope of work (See Appendix A.) Certain specific resource requirements were analyzed in conjunction with the detailed analysis of specific programs. These are presented in the next section. As noted in the executive summary, the panel felt that continued vigorous support of the personnel involved is warranted, with the proviso that the recommendations of Table I be taken into account. The panel did note several instances where tight funding hampered the work. For example, existing capacitor banks were not fully utilized, and existing diagnostics were not consistently used, because of funding constraints.

III: Analysis of the Detailed Presentations on Particle Beam/Compact Toroid Experiments

In this section, we present the Advisory Panel's understanding and analysis of each of the PB/CT programs for which a presentation was made. The purpose of this section is to provide a detailed analysis to help the Division of Applied Plasma Physics, to whom the report is addressed, to formulate its plans with regard to integrating the PB/CT work into the overall Compact Toroid program. It should be emphasized that these comments in no way constitute the results of a review of the specific programs involved -- they are solely an attempt to define how and in what time frame each individual research project can fit into the overall program.

We present, for background information, an estimate of the number, N , of charged particles necessary to produce marginal field reversal. This is the minimum number needed to produce closed field lines, as in Figure 1. This number is a benchmark useful in evaluating the status of each of the particle beam experiments. The radius of the particle orbits which make up the ring is given by $\rho = m v / Bq$, where B is the average field seen by the particle as it executes its orbit. The orbit is in general only approximately circular, and the center of the orbit may not be on the axis of the ring. There is in general a conducting wall which modifies the field seen by the particles. Neglecting the factors which these corrections introduce, and setting B equal to half the applied field, appropriate to marginal field reversal, we find that a certain number of particles, $N = 2 \times 10^7 (m/q^2) \rho$ is required. For a cylinder of length L long compared to its radius, a , the corresponding number is $N = 10^7 (m/q^2) L$ (MKS units are used throughout). Using dimensions of $a = L = 0.1$ meter, and using the above two formulas as estimates for the number of particles needed, we find $N = 6-12 \times 10^6$ protons are needed for field reversal, and twice this number for deuterons. Although these estimates may be overly conservative by a factor of two or three, this number is barely within the capability of existing ion generators. Thus ion ring experiments will involve short, small radius rings of the dimensions indicated until higher current sources or long-pulse sources can be developed. On the other hand, for electrons, with small m/q , existing high-current beam generators are adequate by several orders of magnitude for field-reversal studies, even allowing for inefficient utilization of the electrons (and relativistic-mass corrections to the above formulae, which are less than a factor of 10 for experiments to date).

(A.) The NRL Ion Beam Program

This program, funded jointly by ONR and by APP since 1979, and directed by C. A. Kapetanakis, is intended to use an extremely high-current ion source available at the U. S. Naval Research Laboratory to make a first attempt at creating field-reversed rings by ion injection. The idea is to use a facility (the Gamble-II generator) which is known to produce enough ions to be able to create field reversal, even if the trapping efficiency of ions in the ring was less than perfect. (For electron injection, trapping efficiencies are typically in the 3% - 15% range, although higher values have been achieved under special circumstances.)

The experiments have produced a reversed field configuration on a transient basis. Assuming close to 100% efficiency in utilizing the generated ions, this is consistent with the above estimates of required particle number and measured radii and lengths. The experimental results are in good agreement with computer simulations, which predict not only the large diamagnetic field changes observed, but also the wall losses. The field reversed entity detaches itself from the source and propagates at a high velocity along an externally-imposed guide field. The resulting ion ring has not yet been trapped. It is not yet certain that it is in fact a ring in axial equilibrium -- the observations to date are consistent with either the existence of a ring or a spatial bunching of the rotating ions due to their different time histories (the first ions out of the generators are of lower energy, and may have a higher ratio of rotational to axial velocity, allowing the later ions to catch them). The panel felt that it was of great importance to demonstrate that the ring was in fact holding itself together in axial equilibrium by its own self-field forces. NRL plans to demonstrate this by increasing the field in the cusp region just outside the ion generator, and trapping the field-reversed layer. An alternative suggested by the panel was to observe the propagation along a uniform guide field for several meters and see if the "ring" holds together. Either of these experiments would require a doubling of the size of the capacitor bank which creates the guide field. Such an approach would require a new capital outlay. If the result were to allow the trapping of a long-lived field reversed ion ring, the panel feels that the results would be very worthwhile. NRL feels that definitive results can be obtained within one year if the present level of effort is maintained.

(B.) The Cornell Ion Beam Program

The ion-beam program at Cornell University under the direction of Professors R. N. Sudan and David Hammer has had two main interests -- the study of the generation, propagation, and trapping of weak ion layers (1%-8% of the level needed for field reversal) and the generation of long-pulsed, medium current ion beams. Because the existing ion machines at Cornell cannot produce the number of ions needed for field-reversal, work to date has been forced to proceed with weak rings. This work has produced several interesting physics results (propagation of a well-defined ion ring, reflection of the ring from a magnetic mirror, delineation of the parameter space where plasma currents do or do not partially cancel the primary ion current.) There is a possibility that the existing IREX generator could be upgraded to produce ion rings with field-reversal factors of 30%. This would let Cornell study some of the strong-ring effects (such as self-field distortion of the magnetic field near the ion generator) which have raised questions in the high-current experiments in the past. A promising approach for the future is the development of a long-pulse generator (LONGSHOT) which could produce enough ions for field reversal, using medium-range currents where self-field effects in the generator region would not be important. The panel feels that this is a very important experiment for the long-range

development of the CT program, since it could lead to a relatively inexpensive means of producing either field-reversed ion rings or high-energy ions in the form of weak rings for addition to small-orbit CT's in the hybrid configurations discussed in Section I and Section II. Continuation of the Cornell program at its present level of effort would allow both the IREX and LONGSHOT programs to continue. Any significant reduction would probably force the curtailment of one of these programs, and the panel believes the long-pulse, low emittance experiments to be the most important for the immediate future.

In conclusion, the panel notes the excellent theoretical work that has been done in connection with the Cornell program. Under the directions of Professor R. N. Sudan, tools have been developed to study both the equilibrium and linear stability of ion rings and ion-ring hybrids with small-orbit CT's. This work, including parts of it which have been transferred to other laboratories via Sudan's former students, will play a vital role in the development of compact-toroid theory.

(C.) The Cornell Relativistic Electron Coil Program

The Cornell Relativistic Electron Coil (Ring) Program, under the direction of Professor H. H. Fleischmann, was the first program to produce long-lived field reversed configurations, and has, in the past two years been the first program in the world to produce CT configurations with lifetimes long enough (milliseconds) to allow meaningful tests of plasma confinement and neutral beam sustenance. These tests have not been carried out to date, because, as was shown in presentations at the workshop, atomic physics processes dominate the present experiments, and auxiliary heating is needed to raise the plasma temperature to a level where even classical plasma transport could be observed. The RECE group under H. H. Fleischmann has now assembled auxiliary heating equipment, and should be able to test plasma confinement in FY 81-82 if the present level of effort continues, and if the vacuum conditions in the large RECE-Christa tank do not cause the lifetime to be charge-exchange dominated. The panel noted the outstanding achievements of the RECE program in the past (first long-lived field-reversal, first test of FR configurations in quadrupole magnetic fields, first demonstration that field reversal could be pushed to the values of $\Delta B/B_0 = 1.8-2$ required for meaningful plasma containment experiments, first demonstration of classical particle-ring decay from field-reversed conditions, first and only demonstration to date of CT translation and re-trapping at a new location.) The panel feels that the proposed plasma confinement experiments are of great importance for the CT program. In addition, the panel feels that hybrids of the large-orbit and small-orbit CT approaches can be investigated in the RECE-Christa device in the future.

In addition, the panel notes the good coupling between the RECE theoretical effort (under Prof. R. Lovelace) and the RECE experimental work. Lovelace did the initial theoretical work on ring stability, and the validity of this work has now been cross-checked at several points with computer simulation. In addition, Lovelace and his students have done fundamental work on the equilibrium and particle distribution functions expected in field-reversed particle rings. Several of Fleischmann's students have made basic contributions to the theory of particle ring stability and translation in the presence of plasmas and resistive walls. These results have been carefully compared with the experiments mentioned above.

(D.) The UC Irvine Particle Beam Program

An active theoretical and experimental particle beam program has been pursued at the University of California at Irvine over the last several years, under the direction of Professor N. Rostoker. Reversed-field configurations have been created by currents induced by rotating electron beams, injected into both neutral and pre-ionized gas. This technique is being pursued at both UCI and NRL.

The UCI group proposes the heating of a field-reversed theta pinch by a rotating electron beam. This proposal may prove very useful -- detailed evaluation is required. In addition the UCI group has been studying the possibility of the heating of toroidal plasmas by cross-field ion beam injection. This set of experiments may prove of critical importance -- the possibility of heating CT's via a microsecond-duration ion beam pulse could be valuable for those CT's which have a sub-millisecond lifetime. An active theoretical program has been carried out by Rostoker's group in this area.

(E.) The NRL Rotating Electron Beam Experiment

Field-reversed configurations are created initially by a rotating beam and maintained by long-lived plasma currents induced by the beam as it leaves the system. Experiments with a single beam produced a system with a reversed poloidal field and toroidal field both inside and exterior to the plasma. The poloidal field lines do not close away from the vacuum chamber walls due to the net poloidal current necessary to maintain the toroidal field. The NRL group, headed by Dr. John Sethian, proposes to extend this technique to produce a closed poloidal field-closed current line system by using a second counter streaming electron beam at a slightly larger radius to cancel the net poloidal current. The result is expected to be an elongated spheromak configuration, with relatively sharp skin currents, and the toroidal field confined to the interior of the plasma. Given the degree of control over the ratio of the toroidal to poloidal field, and the ability to form a CT configuration at a large distance from material walls, this should be an important experiment. A continuous variation from the true Spheromak configuration (poloidal field line tension containing toroidal field pressure) towards the high-beta FRC configuration may be achievable by varying the pitch of the beam rotation. The panel discussions brought out the fact that, if the skin currents can be kept sharp and the interior toroidal field relatively low, the resulting configuration might be attractive for alternate fuel reactors. This could represent a significant new direction for the PB/CT program.

APPENDIX A

U.S. DEPARTMENT OF ENERGY
memorandum

DATE May 22, 1980

REPLY TO
ATTN OF ER-753

SUBJECT Proposed Workshop On Particle Beam/Compact Toroid Research (PB/CT Projects).

TO William F. Dove, Chief
Advanced Fusion Concepts Branch
Office of Fusion Energy

Per our discussions, I suggest that we hold a workshop on the particle-beam/compact-torus approaches at Germantown on June 26-27, 1980, for the purpose of exploring the following three issues:

- (1) Which PB/CT projects have the possibility of leading to interesting fusion reactors in their own right? What are the reactor features of each; what are their strengths and weaknesses?
- (2) Which PB/CT projects may have a significant beneficial effect on the rest of the compact-torus program? What possibilities can be identified now? Which may become more important?
- (3) What are the resource requirements to maintain significant progress in the above areas? What are the consequences of level-of-effort activity for the APP/AFC component of these programs?

I have emphasized the connection between the particle-beam experiments and compact toroids because even the high energy ion rings experiments may lead to reactors of compact-toroid geometry, somewhat smaller than Tokamaks, and possibly only slightly larger than the Spheromak reactors (See DOE/ET-0047, May, 1978, Appendix A, Article by H. Fleischmann, R. Sudan, C. Kapetanakis.)

It seems important to integrate this work into the program planning for compact toroidal systems. I am assembling a small panel of advisors to assist in this process. The output of the meeting will be a report with concise (1-2 page) conclusions about the above issues for each of the APP/AFC supported particle beam approaches.

The suggested invitees and agenda are listed on the attached sheets.

W. Condit

William C. Condit, Jr.
Advanced Fusion Concepts Branch
Division of Applied Plasma Physics
Office of Fusion Energy

Attachments

- (1) List of invitees
- (2) Proposed agenda

APPENDIX B

Department of Energy
Washington, D.C. 20545

June 24, 1980

To Those Listed

Subject: Recommendations Needed On Particle Beam/Compact Torus Work

Gentlemen:

At the conclusion of the PB/CT Workshop, I would like you to prepare a short report assessing the state of particle beam work. Please include any recommendations as to the future directions and emphasis of the program which arise from the work presented during the workshop, and your own suggestions and comments. In particular, assessments as to the appropriate lengths of time and levels of activity to obtain significant goals should be included. I will ask Bill Condit, as secretary, to compile this report and send it to you for final approval by approximately July 20, 1980.

Bill

William F. Dove, Chief
Advanced Fusion Concepts Branch
Division of Applied Plasma Physics
Office of Fusion Energy

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FIG. 1: SCHEMATIC COMPACT-TOROID FUSION REACTOR