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SPONSORED PROJECT INITIATION

Date: 1/12/81

Project Title: A Fusion Studies Program

Project No: E-26-670 (NOTE: Continuation of E-26-656)

Project Director: Dr. Weston M. Stacey, Jr.

Sponsor: U.S. Department of Energy; Oak Ridge Operations; Oak Ridge,TN 37830

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(R&D Perf and Rpt Periods)

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Assigned to: Nuclear Engineering (School/~~Laboratory~~)

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Date 3/29/84

Project No. E-26-670

School/~~Lab~~ NE

Includes Subproject No.(s)

Project Director(s) Dr. W. M. Stacey ~~GTRI~~ / GIT

Sponsor Dept. of Energy, Oak Ridge, TN

Title A Fusion Studies Program

Effective Completion Date: 10 /31/81 (Performance) 10/31/81 (Reports)

Grant/Contract Closeout Actions Remaining:

- [X] None
- [ ] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. E-26-656

Continued by Project No. E-26-686

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Georgia Tech Fusion Studies Program

Contract DE-AS05-78ET-52025

Quarterly Progress Report
for October 1 - December 31, 1980

GEORGIA TECH FUSION STUDIES PROGRAM

Quarterly Progress Report, January 15, 1981

Bundle Divertor Studies

A wide variety of bundle divertor designs for a tokamak fusion reactor similar to INTOR were studied in report GTFR-20, which will appear in the Proceedings of the American Nuclear Society 4th Topical Meeting on the Technology of Controlled Nuclear Fusion (King of Prussia, PA, 14-17 October 1980). All the designs provided adequate clearance for neutron shielding and satisfied engineering constraints on the maximum allowable coil stress, cooling requirements, radiation damage and so forth. The best bundle divertor design had a clear throat aperture 0.6 m high by 1.0 m wide and produced a localized magnetic ripple of about 1.2% at the geometric center of the plasma. Smaller bundle divertors with less shielding would produce less magnetic ripple in the plasma, but would be less effective at diverting the edge of the plasma and would not last as long in a tokamak reactor.

A study of hybrid bundle divertors was initiated during November 1980 in an effort to reduce the magnetic ripple while increasing the amount of diverted plasma. Our first hybrid bundle divertor design, which is described in report GTFR-23, reduced the ripple at the center of the plasma to 0.3% while increasing the throat aperture to 1.0 m high by 1.8 m wide. Clearance of about 0.7 m is provided for neutron shielding and coil dimensions. Each of the three parts of the divertor can be pulled out between toroidal field coils for access or replacement. The hybrid divertor has the added advantage of spreading out the scrape off layer (from 0.1 m to 0.7 m) which reduces the local heat flux to the collector plate. Further optimization work is in progress.

Impurity Flow Reversal

A computer analysis of impurity flow reversal in tokamaks caused by co-injection of a neutral beam momentum source was performed using fixed density and temperature profiles. It was found that the impurity flow observed in the PLT and ISX tokamak experiments during neutral beam injection could be explained using this momentum drag model. Analysis indicated that this mechanism would be useful for controlling impurities in an FED sized tokamak reactor. The dependence of the results on beam angle and power was investigated. Part of this work was performed in collaboration with D. J. Sigmar and E. C. Crume at Oak Ridge National Laboratory for the FED project. A detailed description of the basic model appears in report GTFR-21 (December 1980).

Effect of Magnetic Ripple

The development of a computer program package for the calculation of ripple-induced plasma diffusion in realistic tokamak geometry was finished. The package allows for the calculation of the plasma diffusion and thermal conductivity given any tokamak plasma cross section and any magnetic ripple configuration. An optional package for predicting the effect of a poloidal divertor was also developed.

Calculations were made on the effect of ripple induced transport in the ISX tokamak experiment at Oak Ridge National Laboratory. A paper on this subject was presented at the American Nuclear Society Washington meeting. The results indicated that significant ripple transport effects could be induced in the experiment and, in fact, were observed. Ripple induced transport remains as the most important known mechanism capable of controlling the plasma during the burn phase of an ignited tokamak reactor.

E-26-670

GEORGIA TECH FUSION STUDIES PROGRAM

Contract DE-AS05-78ET-52025
Quarterly Progress Report
for January 1 - March 31, 1981

Ripple Reduction Poloidal Field Coils for Tokamaks

Ripple reduction poloidal field (RRPF) coils consist of dipole coils placed above and below the tokamak plasma to produce the vertical field needed for plasma equilibrium and at the same time designed to reduce magnetic ripple from the discrete toroidal field (TF) coils.

An example of an RRPF coil set designed for an INTOR or ETF tokamak reactor is completely described in the attached draft of report GTFR-26. In this particular example, the magnetic ripple from eight TF coils is reduced from more than 2% at the outer edge of the plasma to less than 0.2% over much of the plasma cross section. A patent application is being pursued.

The advantages of ripple reduction poloidal field coils are:

1) Some or all of the poloidal field coils can be placed close to the plasma (just outside the blanket and shielding) without linking the TF coils. Hence less current is needed in RRPF coils than in conventional poloidal field (PF) coil designs placed outside the TF coils. For example, the RRPF coils described in the draft of GTFR-26 require less than five M Amp turns while some of the INTOR PF coils require more than 26 M Amp turns. With less current required, less coil material is needed and they are less expensive. RRPF coils are also made of modular coils which are considerably smaller than conventional PF coils. It should be kept in mind that construction of the Joint European Tokamak is being delayed because it was difficult for European industry to make the very large PF coils used in that design.

2) With the use of ripple reduction poloidal field coils, tokamaks can be designed with fewer TF coils for greater access to the plasma chamber. For example, the design presented in the draft of GTFR-26 uses only eight TF coils while reducing the magnetic ripple to acceptable limits. Alternatively, the TF coils can be made somewhat smaller or the plasma chamber can be made somewhat larger for a given set of TF coils. Costs are reduced and construction is simplified.

3) Magnetic ripple can easily be varied over a wide range for fusion burn control when RRPF coils are used.

Work is in progress to further optimize the design of ripple reduction poloidal field coils for tokamak reactors. The design will be altered to produce the desired vertical and shaping fields needed for plasma equilibrium. An attempt will be made to reduce ripple even further. It is hoped that this idea can be implemented in the next large tokamak to be built by the U. S. Department of Energy.

Impurity Flow Reversal

The theory for impurity flow reversal in tokamaks, caused by co-injection of a momentum source, was extended to a set of equations for a plasma with three disparate mass species in a mixed collisionality regime. This collisionality situation is typical in present day tokamak experiments and is expected to exist in future devices, at least in the edge region. The results are consistant with the previous two species findings reported in GTFR-21 (Dec., 1980). The momentum input to the two lighter species is seen to drive the heaviest species outward, the lightest species inward, and the middle species more slowly inward or outward depending on the relative concentrations and masses of the three species. Extensions of a momentum drag model to fit this situation are being performed and a computer analysis is planned.

Attachment: DRAFT GTFR-26

DRAFT

GTFR-26

Ripple Reduction Poloidal Field Coils for Tokamaks

by Glenn Bateman
Georgia Institute of Technology

March, 1981

Research sponsored by the Office of Fusion Energy, U.S. Department of Energy under contract DE-AS05-78ET-52025 with the Georgia Institute of Technology.

NOTICE

Ripple reduction poloidal field (RRPF) coils consist of dipoles placed above and below the tokamak plasma as shown schematically in Fig. 1 to produce the vertical field needed for plasma equilibrium and at the same time to reduce magnetic ripple from the discrete toroidal field (TF) coils.

One advantage of these coils follows from the fact that they can be placed close to the plasma (just outside the blanket and shielding), within the TF coils, without linking TF coils. As a result, less current is needed to produce the vertical field with RRPF coils than is needed with poloidal field coils placed entirely outside the TF coils. For example, the design presented in this paper requires less than 5 M Amp turns in each RRPF coil compared to 26 M Amp turns in just one of the PF coils in the INTOR design. With less current, power requirements are reduced, less coil material may be used, and the overturning moment on the TF coils is reduced.

Another advantage of ripple reducing poloidal field coils is that fewer TF coils may be used for increased access to the plasma. (Eight TF coils are used in the design presented in this paper.) Also, smaller TF coils, or larger plasma for a given set of TF coils, may be used. Finally, magnetic ripple needed for burn control can be easily varied with RRPF coils.

Coil Design

In the simplest realization of RRPF coils, the dipole coils are placed above and below the plasma and staggered between TF coils as shown in Fig. 1 to reduce ripple. After some experimentation it was found that a more suitable poloidal field through the plasma is produced when the RRPF coils are placed on the outboard side of the plasma as shown in Fig. 2. The inner pair of coils strengthens the vertical field near the midplane while the outer coils produce the radial field needed for axisymmetric vertical plasma stability. These coils are tilted to more uniformly cancel the TF coil ripple over most of the plasma.

Figure 3 shows a top view of the same coils. The coils have long radial extent in order to minimize the current needed for ripple reduction. Each coil is shaped so that it can be pulled out between the TF coils without twisting or shifting. There is enough clearance for superconducting RRPF coils.

Figures 4 and 5 show the reduction in ripple as the RRPF coils are energized with 4.73 M Amp turns current. Ripple is reduced by more than an order of magnitude over much of the plasma cross section, particularly near the midplane. Enhanced transport due to ripple trapped ions virtually disappears over most of the plasma, according to computations similar to those in report GTFR-22 by A. Engel and J. N. Davidson. Further reductions in ripple can probably be achieved by using additional RRPF coils placed directly above and below the plasma. Such coils will be needed in any event to shape the applied poloidal field needed to produce elongation of the plasma.

One concern with the RRPF concept is that the plasma equilibrium will no longer be axisymmetric. However, it is observed that the asymmetry in the vertical field is less than 15% at the outer edge of the plasma on the midplane and much less within the plasma. Further theoretical and experimental investigation may show that problems associated with asymmetry in this case are minor.

In order to achieve independent control of the poloidal field for a given ripple reduction, additional dipoles can be placed in each toroidal sector between those RRPF coils shown in Fig. 3. The difference in current between adjacent dipoles controls the ripple while the net current controls the applied poloidal field.

Figure Captions

Fig. 1. Schematic of ripple reduction poloidal field coils between two toroidal field coils. Directions of current flow and magnetic field are indicated.

Fig. 2. Cross sectional view of an implementation of the ripple reduction poloidal field coils drawn to scale for an INTOR-like tokamak reactor with divertor omitted. It was found that placing the ripple reduction coils on the outboard side of the plasma produces a vertical and radial magnetic field through the plasma suitable for vertical axisymmetric stability while at the same time strongly reducing magnetic ripple. Clearance is left for 1.5 meters of blanket and shielding around the plasma.

Fig. 3. Top view of ripple reduction poloidal field coils in an INTOR-size tokamak reactor with 8 toroidal field coils. Coils indicated with solid outlines are placed above the midplane while those with dashed outlines are below the midplane. Each toroidal field coil carries 17.875 M Amp to produce a 5.5 Tesla field at R = 5.2 m. Each ripple reduction coil carries 4.73 M Amp in this implementation.

Fig. 4. Ripple contours over plasma cross section from the 8 toroidal field coils alone. Here ripple is defined as the computed toroidal field minus the 1/R axisymmetric toroidal field, divided by the toroidal field. The ripple shown here is directly under a toroidal field coil.

Fig. 5. Ripple contours over plasma cross section under a TF coil from 8 toroidal field coils plus the ripple reduction poloidal field coils shown in Figs. 2 and 3 carrying 4.73 M Amp turns of current.

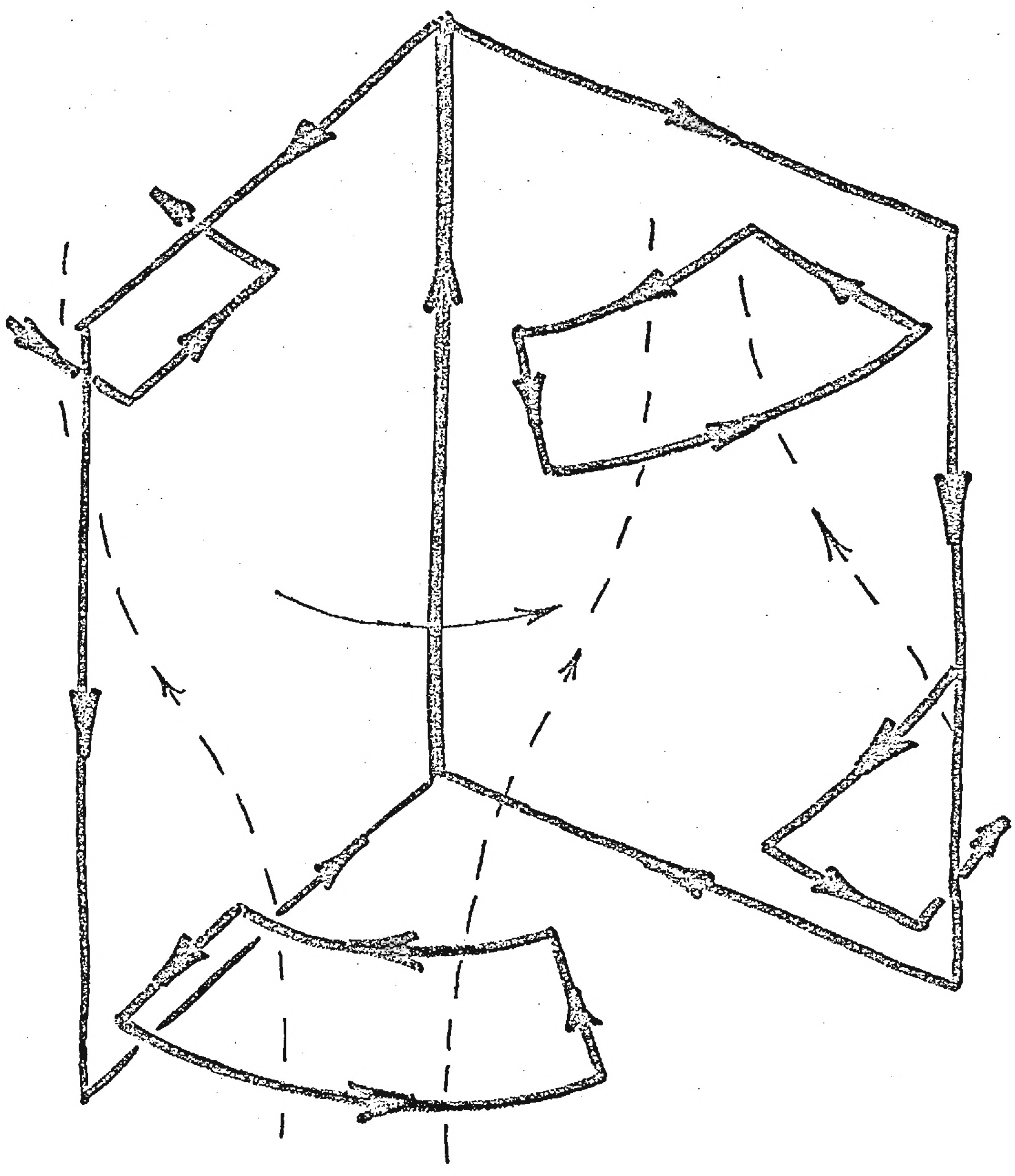

Fig. 1.

Ripple Reduction PF Coils With 8 INTOR TF Coils Cross Section

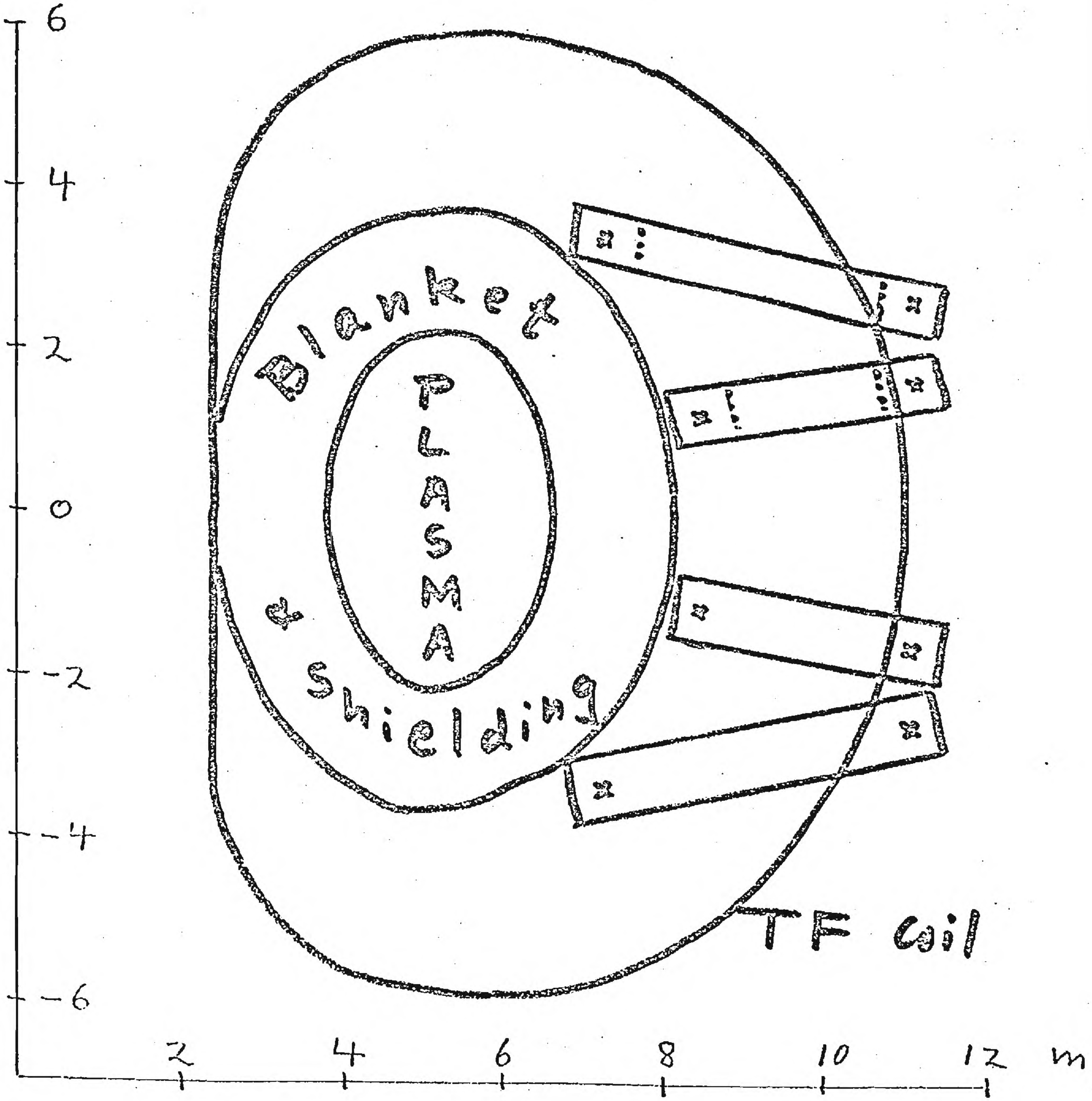

Fig. 2. Bateman March 1981

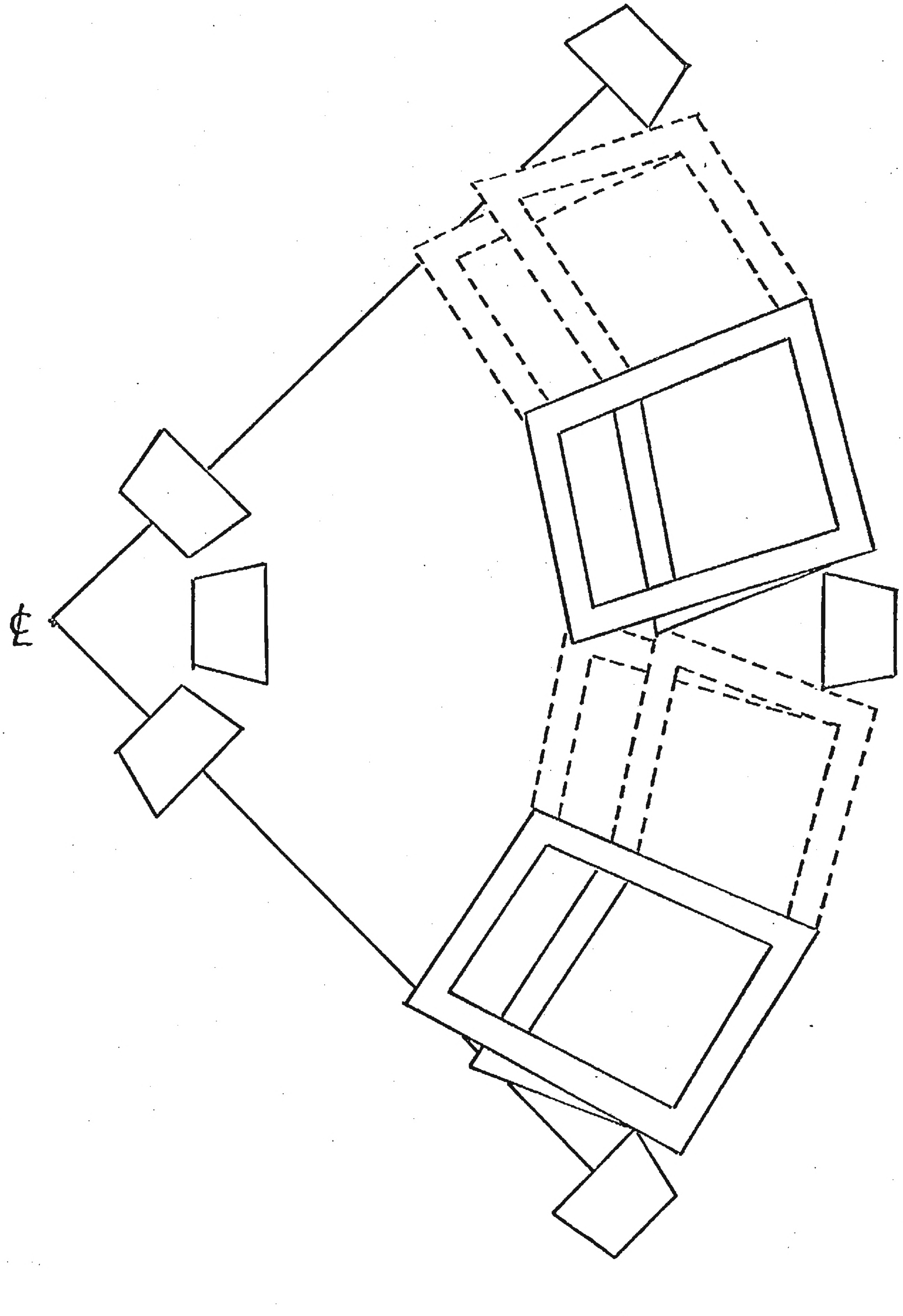

Fig. 3.

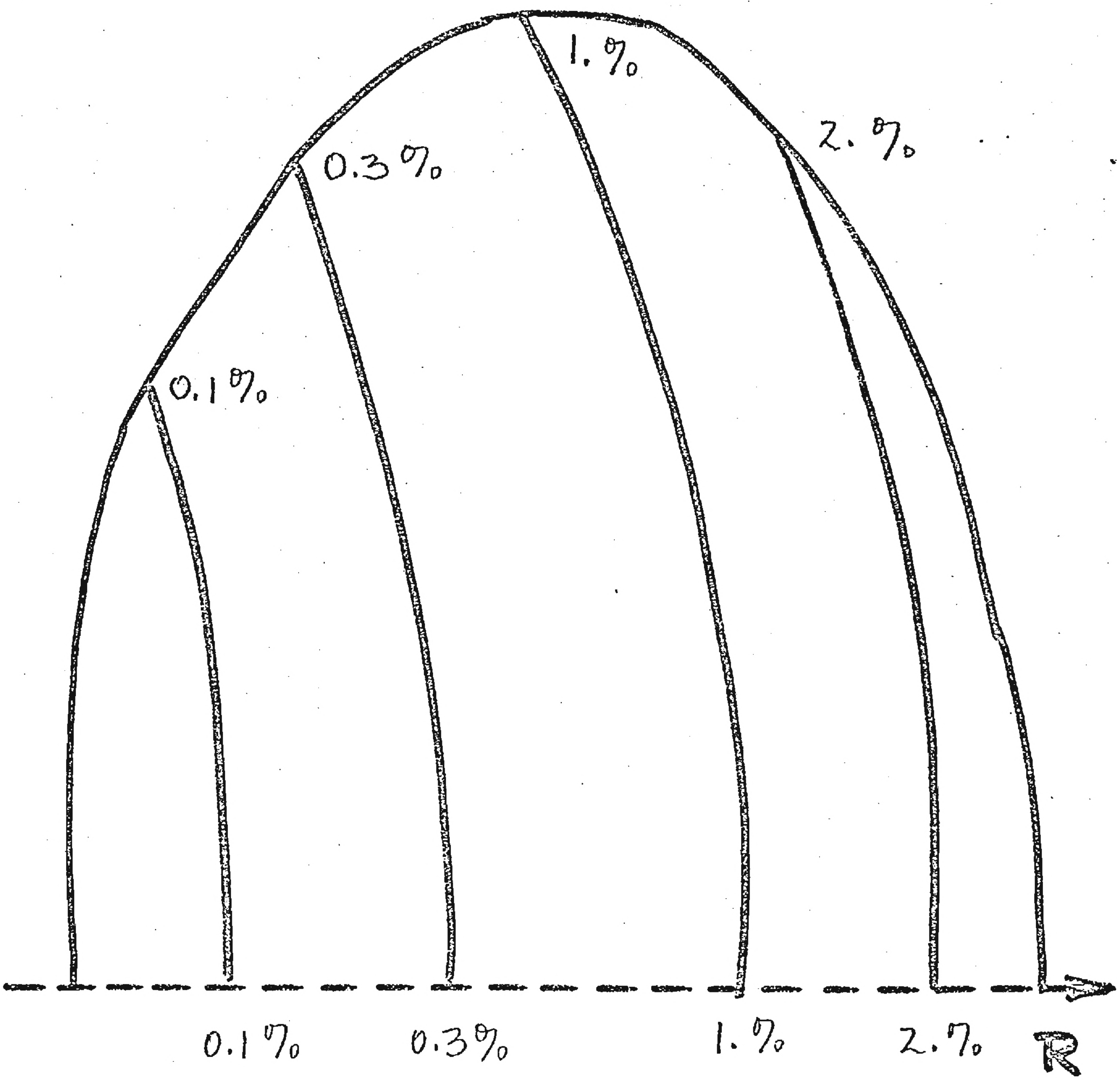

Fig. 4.

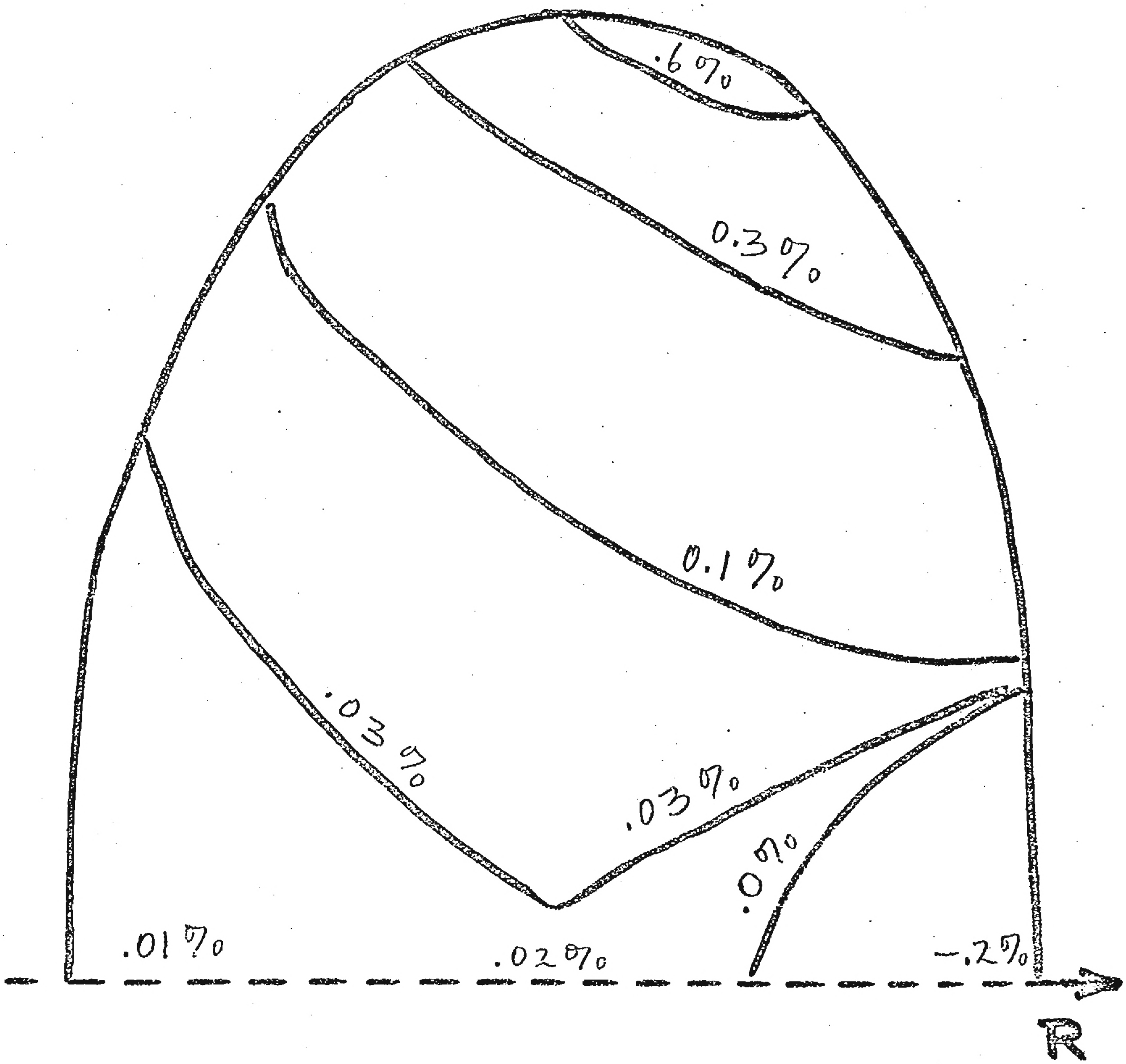

Fig. 5.

E26-670

GEORGIA TECH FUSION STUDIES PROGRAM

Contract DE-AS05-78ET-52025
Quarterly Progress Report
for April 1 - June 30, 1981

Impurity Flow Reversal

Preliminary computer analysis of the Stacey and Sigmar [1] impurity flow reversal theory due to co-injection of a neutral beam was completed. Some extensions to the Stacey and Sigmar theory which were reported in GTFR-21 (December 1981) were included in this analysis. Using fixed density and temperature profiles, the flow reversal theory was found to be a plausible explanation for the argon puff experiments [2] in ISX-B, as well as reduced central radiation in both ISX-B [2] and PLT [3] during co-injection.

Extrapolation of this work to a near reactor sized device, FED, indicates that 10 to 25 MWatt of beam power could have a significant impurity control effect. The FED tokamak reactor was studied with different impurities, beam power, beam energy, and injection angle. As was expected, flow reversal is enhanced with increasingly tangential injection, and increasing beam power. Larger beam energy was found to have only a slight positive effect due to increased beam penetration. The report GTFR-25 details this phase of work, and the report was submitted to Nuclear Fusion for publication.

Further study of the Stacey-Sigmar beam driven flow reversal was initiated using the PROCTR tokamak transport code, partly in collaboration with H. Howe, the code originator. This code resides on the MFE computer network, and consultation on the codes use was done at Oak Ridge National Laboratory. A correction to the transport of a species in coronal equilibrium was added in order to help supplement the usual coronal equilibrium transport of an average charge state. This term takes into account the gradients of each sub-species, and has the form of a gradient in the charge state of the species. This term typically enhances inward impurity transport, and can be significant at low electron temperatures and high electron temperature gradients. The code is in the process of being expanded to include more than one impurity species, since interactions between impurity systems may greatly change a single impurity species behavior.

Ripple Reduction Poloidal Field Coils for Tokamaks

As described in GTFR-26, ripple reduction poloidal field (RRPF) coils are designed to replace some or all of the conventional poloidal field coils and at the same time substantially reduce the magnetic ripple from discrete toroidal field coils. By using a field line following code, it has been determined that the RRPF coil design described in GTFR-26 produces no noticeable departure from axisymmetry in the vicinity of the plasma. Work is now in progress to determine the RRPF coil configuration needed to produce reasonable plasma equilibria in tokamak reactors. With this information from an equilibrium code, further work will continue on the optimization of RRPF coils to minimize ripple subject to both engineering and plasma equilibrium constraints.

References

1. W. M. Stacey, Jr. and D. J. Sigmar, Nuclear Fusion 19, 1665 (1979).

2. R. C. Isler, E. C. Crome, D. E. Arnurius, and L. E. Murray, Oak Ridge National Laboratory report ORNL/TM-7472 (1980).

3. S. Suckewer et al., Princeton Plasma Physics Laboratory report PPPL-1768 (1981).

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GEORGIA TECH FUSION STUDIES PROGRAM

Contract DE-AS05-78ET-52025
Quarterly Progress Report
for July 1 - Oct 30, 1981

Ripple Reduction Poloidal Field Coils for Tokamak Reactors

Glenn Bateman

Ripple Reduction Poloidal Field (RRPF) coils[1] are an arrangement of magnetic coils which produce the vertical and shaping field needed for plasma equilibrium and at the same time reduce the magnetic ripple from the return legs of the toroidal field (TF) coils.

Compared with conventional poloidal field coils designed for tokamak reactors, RRPF coils are relatively small and modular, so that they are relatively easy to manufacture, transport, and replace. They fit within the TF coil set, without having to link TF coils. Since RRPF coils can be placed close to the plasma, just outside the blanket and shielding, they require less current and therefore less coil material, structural support and power to produce a given vertical and shaping magnetic field. Since RRPF coils can be used to significantly reduce magnetic ripple, it becomes possible to design tokamak reactors with fewer TF coils, for greater access, or with smaller TF coils, to reduce cost for a given plasma size. Finally, it is possible to arrange RRPF coils to vary ripple over a wide range for burn control, and independently vary the poloidal field to respond to change in plasma pressure.

By adjusting the current in a given set of RRPF coils, it is possible to null the ripple at a selection of points within the plasma.

In my best design to date, for example, using two sets of RRPF coils in a tokamak reactor design with INTOR dimensions and 8 TF coils, the magnetic ripple is less than 0.01% on the midplane and less than 0.1% throughout the plasma when the current in the RRPF coils is adjusted to 4.5 and 3.2 M Amp turns. I have found that the vertical and plasma shaping fields can easily be adjusted, independent of the ripple reduction, if pairs of adjacent dipole RRPF coils are used. In the case mentioned above, the plasma elongation can also be controlled independent of the vertical field and ripple.

For given examples of RRPF coil sets, the plasma equilibrium has been investigated with the ORNL equilibrium code by D.J. Strickler at ORNL and independently with the PEST equilibrium code with the help of A. Miller at the Princeton Plasma Physics Laboratory. Good examples of free boundary equilibria have been found with each code. There is plenty of freedom to adjust the position and shape of the plasma.

A field line following code has been used to study possible effects of nonaxisymmetry of the RRPF coils. No adverse effects have been found so far. In particular, the field lines are observed to stay on simple toroidal flux surfaces with no magnetic islands or ergodic regions from the field of the RRPF coils.

In conclusion, RRPF coils appear to be a very promising way to avoid having to place large poloidal field coils outside the TF coils. The number of TF coils can be reduced to eight and possible fewer. The current needed for the poloidal field coil system can be substantially reduced. No physics problems have been encountered so far. Work is continuing toward a more detailed optimized engineering design.

Neutral & Beam-Driven Impurity Flow Reversal

W. M. Stacey, Jr. and R. B. Bennett

Some form of active control of limiter sputtered impurities will be required to complement a pump-limiter, which exhausts helium, in FED. The most plausible method suggested to date is momentum - driven flow reversal. Stacey and Sigmar[2] developed a theory for neutral beam driven flow reversal, which stimulated experiments on ISX-13 and PLT. These experiments[3,4] confirmed the prediction that co-injection tends to drive impurities from the center of the plasma.

We completed a preliminary analysis of the impurity flow reversal experiments in ISX-B and PLT during this reporting period, using an extension[5] of the Stacey-Sigmar theory to include temperature gradient effects. Our preliminary analysis indicates that the theory is supported by the experimental results.

Based upon this positive indication, we have applied the theory to FED. We tentatively conclude from the preliminary analysis that neutral beam driven impurity flow reversal could be feasible for FED.

These preliminary analyses were documented[6] during this reporting period. We will undertake a more rigorous analysis as part of our future work under this contract.

References

[1] Glenn Bateman, Georgia Tech Fusion Report, GTFR-26, (March, 1981).

[2] W. M. Stacey, Jr. & D. J. Sigmar, Nucl. Fusion, 19, 1665 (1979).

[3] R. C. Isler, et al., ORNL/TM-7472 (1980).

[4] S. Suckewer, et al., PPPL-1768 (1981).

[5] R. B. Bennett, GTFR-21 (1980).

[6] R. B. Bennett and W. M. Stacey, Jr., GTFR-25 (1981).