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Advanced Fusion Concepts Project Summaries

MASTER

December 1980

U.S. Department of Energy
Office of Energy Research
Division of Applied Plasma Physics
Advanced Fusion Concepts Branch

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Washington, D.C. 20585**

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PREFACE

This report contains descriptions of the activities of all the projects supported by the Advanced Fusion Concepts Branch of the Office of Fusion Energy, U. S. Department of Energy. These descriptions are project summaries of each of the individual projects, and contain the following: title, principle investigators, funding levels, purpose, approach, progress, plans, milestones, graduate students, graduates, other professional staff, and recent publications.

The individual project summaries are prepared by the principle investigators in collaboration with the Advanced Fusion Concepts (AFC) Branch. In addition to the project summaries, statements of branch objectives, and budget summaries are also provided.

This report will be distributed to various segments of the magnetic fusion community. For scientists in the field, it is intended that the report, by providing information about on-going projects, will contribute to communications among the field scientists, and between field scientists and the Office of Fusion Energy.

For the Office of Fusion Energy, the report will contribute to the understanding, coordination, and management of the projects by the Office of Fusion Energy staff.

The Branch hopes to issue similar reports periodically. In the future, the report may be issued shortly after close of the fiscal year and thus serve as an annual report.

Robert S. Shaw
Advanced Fusion Concepts Branch
Division of Applied Plasma Physics
Office of Fusion Energy
Office of Energy Research

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

The Advanced Fusion Concepts Branch Program

Introduction

The Advanced Fusion Concepts Branch of the Division of Applied Plasma Physics has responsibility for managing the advanced concepts program for the Office of Fusion Energy. This responsibility includes building and operating plasma confinement devices to study concepts which are considered alternatives to tokamaks or magnetic mirrors and, in many cases, have unique features. This leads to support of a variety of plasma confinement concepts including a variety of new ideas.

Objectives

The objective of research on alternate concepts is to test magnetic fusion concepts which represent technical alternatives to tokamaks and mirrors. Since there is a high degree of confidence that a burning plasma will be demonstrated in a tokamak, alternate concepts are selected primarily for their potential reactor attractiveness and their technical credibility.

Strategy

The program is managed in a dynamic way. The alternative concepts, generally speaking, are at a relatively early stage of development with attendant high risk of failure. The testing of the most promising alternate concepts will help ensure that the best possible reactor approaches are available for development into commercial reactors. As definitive research results become available for a concept at any stage, a decision will be made to either advance that concept to the next stage or to terminate funding. Funding priorities among the concepts are based on reactor attractiveness, commercial potential, and technical and programmatic considerations. Periodic evaluations of concepts at all stages are conducted to ensure up-to-date information on which to base funding decisions.

Organization

The projects currently supported by AFC are divided into two general categories, concept development and supporting studies.

Among the concept development are:

- Reversed Field Pinch (RFP)
- Compact Toroids (CT)

Among the supporting studies are:

- Alternate Fuels/Multipoles (AF/MP)
- Stellarator/Torsatron (S/T)

Other concept development projects no longer supported by AFC appear in this report. Three additional approaches are then included:

- Linear Magnetic Fusion (LMF)
- Fast Liner
- Tormac

Funding Summary

The following table presents the Advanced Fusion Concepts Branch Operating Budget for fiscal years 1979 and 1980:

	<u>FY 1979</u>	<u>FY 1980</u>
AFC Branch Totals (thousands)	\$19,475	\$ 13,932
RFP	5,025	5,025
CT	4,430	7,331
AF/MP	746	875
S/T	606	320
LINER	727	0
TORMAC	600	35
LMF	1,825	0
EBT*	4,930	0
Other	586	346

* EBT has been transferred to the Division
of Mirror Confinement Systems

Project

Toroidal Reversed-Field Pinch ZT-S

D. A. Baker

FY 79	\$ 550K	op.	FY 80	\$ 0	op.
	\$ 50K	eq.		\$ 0	eq.

Purpose

The proposed use of ZT-S is to augment the RFP program by investigating reactor oriented physics and engineering issues. In particular, ZT-S will investigate the effects of the finite resistivity and segmentation of the stabilizing shell on the transport and heating of the toroidal reversed-field pinch and help develop methods to correct the above effects.

Approach

RFP plasma-field configurations having favorable stability properties are produced in a 15-cm toroidal vacuum chamber. Heating is obtained ohmically from the large current density in the plasma.

Progress

A new, interesting low density ($n \sim 4 \times 10^{14} \text{ cm}^{-3}$) RFP operating regime has been found, and pressure balance calculations from magnetic probe data indicate that increased temperatures may be present with this low density operation. Thomson scattering measurements have yet to be completed. Two varieties of acoustic pressure probes have been tested on ZT-S and they indicate the presence of significant wall pressures during RFP start-up. Bellows sections to replace the present ceramic torus by a metal liner were procured during this period.

Plans

The immediate plans are to complete the Thomson scattering electron temperature measurements for the low density operation. In view of the reported success of operating small RFP's with slow start-up using metal liners (e.g., the 20-cm bore TPE IR(M) experiment in Japan), it is planned to determine if a metal liner will allow a quiescent operating following a slow start-up in ZT-S. If successful, ZT-S will be used to do parallel experiments and materially shorten the time necessary to answer physics and engineering questions that would normally require a series of experiments on ZT-40. While the ZT-S metal liner is being fabricated, a more energetic slow capacitor bank will be installed. The metal liner will be installed when its fabrication is complete. If suitable quiescent operation is achieved, a set of experiments designed to obtain answers to the following fusion reactor oriented questions will be undertaken:

1. What are the effects on the equilibrium and its stability of the diffusion of magnetic fields into the shell?
2. How can field correction and slow feedback stabilization with segmented metal shell be implemented to correct the effects in the previous question?
3. Can effective methods for DC drive of the toroidal current be developed for the RFP?

The first question can be studied by operating ZT-S with a resistive stabilizing shell (or even no shell) and an additional vertical field. Studies of feedback stabilization applied to a segmented stabilizing shell will address the second question. The third question can be studied on ZT-S using the concept of an rf-driven current.

Milestones

1. Measure electron temperature.	Oct. 1980
2. Install new capacitor bank.	Feb. 1981
3. Install metal vacuum liner and field windings.	March 1981
4. Begin the study of the operation with slow start-up and metal liner.	May 1981
5. Decision point to proceed with conversion to resistive shell.	Oct. 1981

Graduate Students (% DOE Support)

None

Other Professional Staff (Part-Time)

L. C. Burkhardt, A. Haberstich, R. B. Howell, A. R. Jacobson, K. McKenna, and A. E. Schofield.

Consultant

T. M. York, University of Pennsylvania

Major Recent Publications

1. A. R. Jacobson, L. C. Burkhardt, D. A. Baker, R. B. Howell, A. E. Schofield, and A. G. Sgro, "Pitch Programming of the ZT-S Reversed-Field Pinch Experiment," 9th European Conf. of Controlled Fusion and Plasma Physics, Oxford, England, Sept. 17-21, 1979.
2. A. R. Jacobson, "Experiments on the ZT-S Reversed-Field Pinch, (August-December 1978)." Los Alamos Scientific Laboratory Report LA-7862-MS.
3. T. M. York and R. B. Howell, "Direct Measurements of Wall Plasma Pressure and Comparison with Magnetic Field Measurements in the ZT-S Toroidal Reversed-Field Pinch," Third Topical Conference on High Temperature Plasma Diagnostics, Los Angeles, California, March 17-19, 1980.

Project

Toroidal Reversed Field Pinch ZT-40

J. N. DiMarco, D. A. Baker, K. S. Thomas

FY 79	\$ 4250K op.	FY 80	\$ 4825K op.
	\$ 350K eq.		\$ 197K eq.

Purpose

ZT-40 is a new experiment in the LASL series of experiments designed to investigate the properties of the MHD stable toroidal reversed-field pinch confinement approach to magnetic fusion. The object is to determine the physics of the formation, heating, and transport needed to design future scaled-up experiments leading to the fusion reactor goal.

Approach

MHD stable toroidal reversed-field configurations are produced by controlling the externally applied magnetic and electric fields and exploiting the natural tendency of the pinch to produce and sustain a reversed toroidal field in the outer region of the discharge. Theoretically, this approach yields the possibility of ohmic heating to ignition with low magnetic fields, since the pinch is not constrained to operate below the Kruskal-Shafranov limiting current, ZT-40 has been designed to operate over a wide range in current risetime and current density in order to optimize the study of ohmic heating, confinement, and methods for setting up the desired magnetic field configurations. The experiment is presently operating with plasma current up to 600 kA with a risetime of 0.1 ms.

Progress

- 1) Obtained plasma currents up to the design value of 600 kA, with a risetime of 0.1 ms.
- 2) Determined background impurity level of $\sim 1\%$ oxygen.
- 3) Observed burn-through of oxygen impurities.
- 4) Implemented measurements of plasma density with seven-chord interferometer.
- 5) Measured the electron temperature on axis, at the time of peak current, to be ~ 100 eV, as predicted by computer simulations based on ohmic heating of the plasma.
- 6) Determined the variation of electron temperature and density on axis as a function of peak plasma current and initial gas fill.
- 7) Demonstrated the formation of reversed-field configurations by both self-reversal and aided-reversal techniques.
- 8) Extended the toroidal current decay time to ~ 0.5 ms by means of a power crowbar system.
- 9) Established operation with reduced magnetic field fluctuations (quiescent periods) with the reversed-field configuration.

Plans

- 1) Operation with a power crowbar in the toroidal field circuit to extend in time both the plasma current and the quiescent period.
- 2) Measure the radial profile of T_e .
- 3) Explore methods of setting up the RFP configuration.
- 4) Measure the total energy loss rate.
- 5) Test the effect of reducing the magnetic field errors at the location of the pumping ports.
- 6) Obtain differential measurements of soft x-ray radiation from plasma.
- 7) Install a metal vacuum wall and make comparisons between operation with a metal and a ceramic vacuum wall.
- 8) Change the risetime of the plasma current to 0.25 ms.

Milestones

1) Operation with I_0 power crowbar to extend the quiescent period.	September 1980
2) Operate with plugged pump ports to reduce magnetic field errors.	September 1980
3) Measurements of radial temperature profiles as functions of time.	October 1980
4) Measurements of total energy loss from plasma.	October 1980
5) Install metal vacuum wall.	November 1980
6) Start operation with metal vacuum wall.	January 1981
7) Evaluate effect of metal vacuum wall on start-up loss.	March 1981
8) Investigate techniques (self reversal and aided reversal) of establishing reversed-field condition with metal vacuum wall.	May 1981
9) Determine electron temperature, electron density profiles, impurity type and concentration with current duration of ~ 3 ms.	July 1981
10) Determine energy containment time as a function of experimental parameters.	September 1981

Graduate Students

None

Graduates

None

Other Professional Physics Staff

(Full Time) C. J. Buchenauer, L. C. Burkhardt, J. N. Downing, Jr., A. Haberstich, R. B. Howell, A. R. Jacobson, E. M. Little, G. Miller, A. E. Schofield, R. G. Watt.

(Part Time) R. R. Bartsch, M. D. Bausmann, C. A. Ekdahl, Jr., P. R. Forman, K. B. Freese, F. C. Jahoda, J. A. Phillips, R. E. Siemon, P. Weber.

Major Recent Publications

D. A. Baker et al., "Initial Reversed Field Pinch Experiments on ZT-40 and Recent Advances in RFP Theory," Eighth Int. IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium (1980). Paper L-2-1.

Guthrie Miller, "Stability of the Noncircular Screw Pinch," accepted for publication in Physics of Fluids.

A. R. Jacobson et al., "Physics Results from the First Six Months of ZT-40 Operation." Presented at 1980 IEEE International Conf. on Plasma Science, May 19-21, 1980, University of Wisconsin-Madison, Madison, WI.

A. R. Jacobson, "A Simple Model for an Upper Bound on Density Fluctuations in a Turbulent Pinch," LA-8198-MS.

Guthrie Miller, "Force Free Equilibria in Toroidal Geometry," LA-UR-80-149. (Submitted for publication to the Physics of Fluids.)

Leaf Turner, "Rigid Draft Magnetohydrodynamic Equilibria for Cylindrical Screw Pinches," Phys. Fluids 22, 727 (1979).

David Montgomery, Leaf Turner, and George Vahala, "Most Probable States in Magnetohydrodynamics," J. Plasma Physics 21, 239 (1979).

R. A. Gerwin, "Global Properties of Ohmically Heated Reversed-Field Pinches," Proceedings of Course held at the International School of Plasma Physics, Varenna, Italy, Commission of the European Communities report EUR FU BRU/XII/475/80, Vol. I, p. 339 (1979).

Leaf Turner, "Relaxation of Toroidal Discharges," Symposium on Compact Toruses and Energetic Particle Injection, Princeton, N.J. (1979).

Richard A. Gerwin, "Some Properties of the Reversed-Field Z Pinch: An Overview." LA-7798-MS (1979).

R. A. Webel, R. L. Hagenson, R. W. Moses, and R.A. Krakowski, "Comparison of Zero-Dimensional and One-Dimensional Thermonuclear Burn Computations for the Reversed-Field Pinch Reactor (RFPR)," LA-8185-MS (1979).

E. J. Caramana, "Startup of the Reversed Field Pinch in an Adiabatic Manner." (Submitted for publication to the Journal of Nuclear Fusion.)

E. J. Caramana, F. W. Perkins, "The Role of Impurities in Producing Thermal Instability in Ohmically Heated Plasmas." (Submitted to the Journal of Nuclear Fusion.)

E. J. Caramana, F. W. Perkins, "Effects of Impurity Radiation on Reversed-Field Pinch Evolution." (Submitted to the Journal of Nuclear Fusion.)

Project

Component Development

R. F. Gribble, C. F. Hammer

FY 79	\$ 225K op.	FY 80	\$ 200K op.
	\$ 10K eq.		\$ 9K eq.

Purpose

The purpose of the Component Development Program is the development of advanced technology needed for advanced fusion concept experiments. Because of the changing nature of the program and limited resources, most of the work is concentrated on critical components needed in one to two years. The technical approach consists of an iterative process of design, fabrication, testing, debugging, evaluation, and modification or redesign. The effort involves analytical and numerical analyses as well as hardware testing. At present, the systems and components' development areas are:

- I. ZT-40 Program
- II. Compact Toroid (CT) Program
- III. International Cooperation on RFX
- IV. Components for Future Experiments

Approach

The approach for a particular project depends on the resources available, the time allowed for development, and the nature of the project. If the schedule permits, a component development project may be carried out sequentially where each configuration (if more than one is necessary) is carried through the process in parallel, provided sufficient resources are available.

Progress

I. ZT-40 program

With the change in the ZT-40 program from 4 kV, fast risetime operation to slow risetime, 10 kV systems, demands on components were greatly reduced. High coulomb rating ignitrons can be used rather than spark gaps.

1. Power Crowbar Transformer

Power crowbar transformers are required to transform voltage and current from the efficient, cost effective 10 kV power crowbar capacitor banks to that required for sustaining the toroidal and poloidal fields. A ZT-40 poloidal field prototype power crowbar transformer was successfully tested to full current in normal and fault modes (open secondary). A ZT-40 scale toroidal field power crowbar transformer was fabricated and tested. Development of these transformers is essentially complete.

2. Toroidal Field Coil Current Joints

Reliable connections are required for the toroidal field winding where the center conductor of the coaxial cable forming the winding ties to the return outer braid. Development and tests were carried out resulting in a new current joint design.

3. Metal Vacuum Liner

A metal vacuum liner is necessary for experiments on ZT-40 as well as a backup to the alumina torus in the event of vacuum or impurity problems. The design of an inconel liner was carried out, and delivery is expected in October, 1980.

4. Power Oscillators

A 100 MHz, 200 kW oscillator is being fabricated for use on ZT-40. Its prime function is the reduction of impurity levels by improvement of the alumina surface vacuum condition. A second oscillator at about 600 MHz, 100 kW peak power, 2 kW average power is being developed by Varian. Employing a simple UHF triode vacuum tube in a resonant cavity, this oscillator will excite a simple toroidal resonance in the torus allowing simple J-loop coupling. Since the mode has an electric field maximum on the axis it should improve plasma preionization. This oscillator will also provide RF glow discharge cleaning of the ceramic torus. The unit can be used with a metal vacuum liner.

The 100 MHz power oscillator modulation section was completed and passed tests. A 600 MHz oscillator development contract was initiated with industry. Delivery is expected in September, 1980.

5. Multiturn Poloidal and Toroidal Field Systems

A multiturn poloidal field (PF) coil has a considerable advantage over the present one-turn or four-feed arrangement driving the ZT-40 shell in that external resistive losses are greatly reduced. Series connected start and crowbar ignitrons will be used with the ZT-40 50 kV banks to drive the coils. Using the 50 kV banks for the multiturn coils, provides a plasma current decay time almost completely determined by the plasma rather than the external circuit as is presently the case. Design of multiturn poloidal and toroidal systems will be completed in September 1980.

II. Compact Toroid (CT) Program

1. Puff Gas Valve

A fast puff gas valve is required for the CT experiments involving the field-reversed theta-pinch. To optimize conditions leading to extended energy confinement time in these experiments, it is necessary to minimize background neutral gas that can cool the plasma after formation and/or during translation. If only the vacuum vessel volume within the theta pinch coil were filled to the proper density, and were subsequently completely ionized and heated by the theta pinch, the requirement for low background neutral gas would be met. A puff gas valve, Model C, has been developed.

2. CTX Start and Crowbar Switches and Triggering System

For the CT program start and crowbar gaps and triggering system improvements over the Scyllac design are necessary to obtain more reliable performance and to be able to operate the capacitor banks to lower voltages than was possible on Scyllac. Such improvement is required for program flexibility. The approach involves the use of the staged theta pinch trigger systems and the modification of start gap insulators so that the gaps will retain the voltage hold-off capability while providing operations at lower voltage. Both the CTX start and crowbar gap development is complete.

3. Mirror Coil Current Connections

Improved current joint connectors for the CT mirror coils have been developed. The improved connectors are to minimize conductor failure and machine down time.

III. International Cooperation on RFX

1. Toroidal Field System

The toroidal field system design requires much numerical simulation to determine optimum designs. The optimum configuration consists of magnetic energy storage with a transfer capacitor to reverse the current, and a flat-top supply to sustain the field at the wall. Design of the RFX toroidal field system is underway.

2. Poloidal Field System

The poloidal field system design is more demanding than the toroidal field system in that much more energy is stored, accuracy of control is more important, and problems of field errors are much more severe. Circuit simulation is necessary to evaluate limits of circuit parameters for reliable performance and the meeting of operating parameters. System response to plasma disruption models, and circuit fault modes must be evaluated. A fault protection system must be designed that will minimize damage to all parts of the experiment in the event of all types of failure modes. The design of the poloidal field system is being performed.

IV. General and Future Development

A joint program with E-Division at LASL has been initiated with the use of Laboratory research funds to develop:

1. High energy density, high reliability capacitors having application to the CT program.
2. Glow discharge, thyatron-like, opening switches that will replace vacuum or other mechanical interrupting switches. This gas opening switch will be much more reliable and less expensive than mechanical devices. The switch will be developed in cooperation with industry and tested at LASL. Applications include all magnetic energy transfer systems with possible near-term use in the RFX experiment.
3. Mechanical magnetic energy transfer elements that can provide greatly increased efficiency in magnetic energy transfer systems for pulsed devices with periods from one to several hundred.

Milestones

I. ZT-40 Project

1. Installation and evaluation of power oscillators.	Dec. 1980
2. Multiturn PF and TF coils and power supply design completed.	Sept. 1980
3. Multiturn PF and TF system installed.	Dec. 1980

II. International Cooperation on RFX

1. Toroidal field system design completed.	March 1982
2. Poloidal field system design completed.	Sept. 1982

III. Components for Future Experiments

Evaluation of the usefulness of advanced capacitor, gas opening switches, and mechanically variable inductors completed.	Sept. 1982

Graduate Students

None

Graduates

None

Other Professional Staff

(Full Time) J. Melton, K. Schoenberg, J. Galbraith, C. Hammer

Major Recent Publications

1. K. J. Kutac, E. M. Little, and W. C. Nunnally, "ZT-40 Engineering Prototype," 8th Symposium on Engineering Problems of Fusion Research (1979).
2. R. W. Kewish and G. Boicourt, "High Voltage Pulsed Cable Design: A Practical Example," 8th Symposium on Engineering Problems of Fusion Research (1979).
3. R. T. Buck, J. D. Galbraith, and W. C. Nunnally, "Low Leakage, High Current Power Crowbar Transformers," 8th Symposium on Engineering Problems of Fusion Research (1979).
4. R. S. Dike and A. Haberstich, "Ceramic Toroidal Vacuum Chamber for the ZT-40 Experiment," 8th Symposium on Engineering Problems of Fusion Research (1979).
5. J. D. Galbraith, "Light Activated 10 kV low Jitter Pulser," 2nd International Pulsed Power Conference (1979).
6. CTR-Division Annual Report, 1979.
7. CTR-4 Quarterly Report for 1st, 2nd, and 3rd Quarters of 1979.

Project

Field Reversing Ion Rings

C. A. Kapetanakis

FY 79	\$ 220K op.	FY 80	\$ 250K op.
	\$ 0K eq.		\$ 0K eq.

Purpose

1. To test the feasibility of forming field reversed proton rings by trapping a large number of energetic protons in a magnetic mirror field.
2. To develop efficient pulsed ion sources that can generate very high current ion beams.

Approach

A hollow, intense proton beam is generated by a low inductance coaxial inverse reflex tetrode (IRT) powered by the Gamble III generator. After passing through a magnetic cusp the proton pulse is trapped inside a magnetic mirror with the aid of a gate field.

Progress

1. Proton pulses of approximately 50 nsec duration containing in excess of 6×10^{16} protons have been generated with low inductance coaxial inverse reflex tetrodes. At 1.5 MeV the peak proton current is about 400 kA.
2. The proton pulse is almost current neutralized along but not across the magnetic field lines. Azimuthal current neutralization can be obtained by letting the beam interact with 100 mTorr of neutral gas.
3. Transient field reversal has been achieved by the propagating proton pulse in both uniform and ramped magnetic fields. The maximum observed field reversal factor $\Delta B/B_0$ is 150%.

Plans

1. Continue the trapping studies of the pulse at higher v_A/V_{th} ratio.

Milestones

1. Sharpening of the transition width of the cusp.	Oct. 1980
2. Reflection of proton pulse by a single mirror.	Jan. 1981
3. Trapping studies using the gate field.	March 1981

Graduate Students (% DOE Support)

None

Graduates

None

Other Professional Staff

J. Golden
S. J. Marsh
J. Pasour
D. Pershing

Major Recent Publications

1. Phys. Rev. Lett. 44, 1218 (1980).
2. Appl. Phys. Lett. 36, 646 (1980).
3. NRL Memorandum Report 4135, December 1979.
4. Proc. 8th Intern. Conf. on Plasma Physics and Contr.
Nuclear Fusion Res., Brussels, 1980 paper #IAEA-CN-38 IR-4.

Project

Field-Reversed Electron and Ion Rings for the Confinement and Heating of Plasmas

Hans H. Fleischmann

FY 79	\$ 285K op.	FY 80	\$ 270K op.
	20K eq.		0K eq.

Purpose

Experimental investigation (with limited theoretical support) into the feasibility of generating and using rings of high-energy electrons and/or ions for plasma confinement and heating.

Approach

Magnetic mirror devices are utilized for injection and trapping of high-current electron and ion beams to test the generation, compression, stability and confinement capabilities of field-reversing charged particle rings. First, comparatively less expensive and technologically simpler electron ring investigations are performed to obtain, by scaling, sufficient base information on the generation and behavior of high-energy ion rings to be used for hot plasmas. (Present experiments are performed mostly on RECE-Christa; RECE-Christa - magnetic field up to 1 kG, injection currents up to 150 kA, electron energies up to 5 MeV.)

Progress

1. Test experiments on the induction of plasma currents in the rings showed good ring stability for plasma currents up to a few hundred amperes.
2. The confinement tank was extended axially by 1.20m to permit ring investigations over longer times and at smaller background pressures.
3. Using ethane puffing, field-reversing rings have been generated upstream and moved over the full distance into the new well region having background pressures $\leq 10^{-4}$ Torr. The ring behavior still appears stable.
4. A detailed analysis of the ring behavior during translation indicates good agreement with theoretical models including resistive currents induced in the background plasma.
5. New theoretical results include among others strong domination of large-orbit particle distribution by non-ergodic particle orbits and the existence of new disc-like equilibria.

Plans

1. Extensive measurements on the confinement of plasmas in field-reversing rings with plasma currents $I_p \ll I_{fast}$ using optical diagnostics.
2. Similar experiments using laser scattering.
3. Investigations of plasma confinement and ring stability in rings with sizable plasma currents.
4. Experiments with decreasing toroidal fields to study transitions to Spheromak-type field geometries.
5. Plasma heating using 1 keV neutral atom beams.

Milestones

1. Complete extension of confinement tank (March 1980, completed).
2. Completion of detailed ring translation measurements (September 1980).
3. Initiation of plasma measurements at gas pressures below 1 mTorr (October 1980).
4. Initiation of experiments with decreasing toroidal field (April 1981).

Graduate Students (% DOE Support)

D. J. Rej (100, Ph.D.), M. Parker (100, Ph.D.), W. LaRoza (20, Ph.D.)

Graduates (year, employed in fusion)

D. M. Woodall (1976, yes), A. C. Smith, Jr. (1977, yes), R. A. Meger (1977, yes), S. Zweben (1977, yes), S. C. Luckhardt (1980, yes), and D. A. Larrabee (1980, yes)

Other Professional Staff

R. Jayakumar, D. Taggart

Major Recent Publications

1. "A Reanalysis of Exponential-Rigid-Rotor Astron Equilibria," R. V. Lovelace, D. A. Larrabee and H. H. Fleischmann, Phys. Fluids 21, 863 (1978).
2. "Recent Results and Work on Field Reversing E- and P-layers," M. Tuszewski et al., 7th International Conference on Plasma Physics and Controlled Thermonuclear Research, IAEA, Innsbruck, Austria, 1978. Paper CN-37-S-4.
3. "Axial Translation of Field Reversing E-Layers," D. J. Rej et al., Appl. Phys. Lett. 33, 910 (1978).

4. "Truncated Exponential Rigid-Rotator-Model for Strong Electron and Ion Rings," D. A. Larrabee et al., Nuclear Fusion 19, 499 (1979).
5. "Magnetic Field Distribution and Image Field Index for Short E-Layers," D. M. Woodall, et al., Phys. Fluids 22, 155 (1979).
6. "On the Theory of Astron Equilibria," R. V. Lovelace, D. A. Larrabee and H. H. Fleischmann, Phys. Fluids 22, 701 (1979).
7. "Kinetic Theory of Ion Ring Compression," R. V. Lovelace, Phys. Fluids 22, 542 (1979) (in part).
8. "Ion Ring Dynamics and Angular Momentum Conservation," R. V. Lovelace, Phys. Fluids 22, 591 (1979).
9. "Precession and Kink Motion of Long Astron Layers," R. V. Lovelace, Phys. Fluids 22, 708 (1979) (in part).
10. "Experiments on the Translation and Compression of Field-Reversing E-Layers and Generation of Superdense MeV-Proton Beams in a Magnetically Insulated Diode," H. H. Fleischmann, D. J. Rej, M. Tuszewski and S. C. Luckhardt, Collective Methods of Acceleration, eds. N. Rostoker and M. Reiser (Harwood Academic Publishers, 1979), p. 699.
11. "Adiabatic Magnetic Compression of Field-Reversing E Layers," M. Tuszewski, D. J. Rej and H. H. Fleischmann, Phys. Rev. Lett. 43, 449 (1979).
12. "Particle Orbits in Ion Rings: Ergodic or Not?" D. A. Larrabee and R. V. Lovelace, Phys. Fluids 23 (1980).

Project

Intense Ion Beam Sources and Applications to Controlled Thermonuclear Research

R. N. Sudan, D. A. Hammer, B. R. Kusse

FY 79 \$ 149K op. FY 80 \$ 150K op.

 \$ 22K eq. OK eq.

Purpose

To produce strong ion rings and study their properties.

Approach

Intense ion beams from an annular ion diode are injected through a magnetic cusp to form a rotating hollow proton layer. This layer is trapped in a magnetic mirror by the dissipation of its axial kinetic energy in a resistive wall.

Progress

1. In the pilot experiment an intense proton beam from an annular magnetically insulated ion diode has propagated through a cusp to produce a rotating proton layer containing 2×10^{14} protons 35 cm downstream of the diode.
2. A 2-D particle simulation code has shown that high trapping efficiencies are possible for ion pulses that exceed 10^{16} protons per pulse.
3. The IREX system, which consists of (i) 800 kV, 7 ohm, 100 nsec pulsed power generator; (ii) a 2.5 m long, 48 cm bore, 12 kG solenoid; and (iii) an annular ring diode; is operating. This system is delivering 10^{15} protons into a rotating ring beam, radially confined by a 8 kG axial field.
4. A ring with very little axial dispersion is produced when the ring is injected into ≥ 50 mT H_2 or ≥ 15 mT air. It propagates the full system length with well defined inner and outer radii of 7 and 13 cm, respectively. Up to 83% of the 400 keV beam kinetic energy is in rotation.
5. Reflections of $\geq 50\%$ of the rotating beam is reflected from a 23% downstream mirror with an air fill, apparently aided by ring axial energy loss to induced azimuthal plasma currents. Such currents are not observed in hydrogen.

6. In hydrogen, rings with temporal full-width-half-maximum of 100 nsec propagate through the system implying that the beam coalesces into a proton ring axially confined by its own 3% diamagnetic well which contains $> 5 \times 10^{15}$ protons.
7. Diamagnetic signals up to 875 G have been observed near the upstream mirror.
8. A long pulse magnetically insulated diode has been developed which produces 600-700 nsec, 100 keV, 10 kA peak current ion beams. It has been combined with a 2 m long drift chamber and 5 kG magnetic solenoid to form the LONGSHOT experiment.
9. Up to 3×10^{16} protons are injected into a ramp shaped solenoidal magnetic field, and spatial bunching of the beam has produced diamagnetic signals of $>3\%$.

Plans

1. Boost the proton output of the IREX diode by at least a factor of 3 in order to allow trapping by axial energy dissipation in a resistive wall.
2. Perform trapping experiments using the boosted IREX proton beam.
3. Use the LONGSHOT beam to investigate the generation of strong diamagnetic proton layers.
4. Install a plasma source on LONGSHOT to facilitate beam propagation.
5. Use the plasma source on IREX to determine if it can eliminate the need for 15-400 mT of neutral gas fill.
6. Determine the life time and stability of the trapped proton ring as a function of background gas pressure, mirror field shaping, etc.
7. Investigate (i) the compression of a proton ring by a pulsed axial magnetic field and (ii) effect of a toroidal field on ion ring behavior.

Milestones

1. Investigate LONGSHOT beam propagation under various diode and solenoidal magnetic field conditions. October 1980
2. Produce $\gtrsim 2 \times 10^{16}$ protons with the IREX diode. December 1980
3. Investigate LONGSHOT beam propagation with plasma in the drift chamber. February 1980
4. Perform trapping experiments on IREX using the increased IREX beam. June 1980
5. Investigate the trapping of proton rings produced by LONGSHOT. July 1980

Graduate Students (% DOE Support)

M. Gaydar (50%)

Graduates

P. Dreike

Other Professional Staff

Research Associate J. B. Greenly (50%)

Postdoctoral Associate K. O. Busby (100%)

Major Recent Publications

1. "Cornell Intense Ion Beam Program", Proc. 2nd Int'l. Topical Conf. on High Power Electron & Ion Beam Res. and Tech. (Cornell Univ., 1977), Vol. I, p. 37. (P. L. Dreike et al.)
2. "Production and Propagation of Rotating Proton Beams Using Magnetically Insulated Diodes", Proc. IEEE Int'l. Conf. on Plasma Science (Monterey, CA, 1978). (P. L. Dreike et al.)
3. "Recent Results and Work on Field-Reversing E- and P-Layers", Proc. IAEA VII Int'l. Plasma Physics and Controlled Nuclear Fusion Research Conf. (Innsbruck, Austria, 1978). (M. Tuszewski, et. al.)
4. P. L. Dreike, D. A. Hammer, R. N. Sudan, L. G. Wiley, Phys. Rev. Lett. 41, 1328 (1978).
5. "Cornell Intense Ion Beam Program", to be published in Proc. 3rd Int'l. Topical Conf. on High Power Electron & Ion Beam Res. and Tech. (Novosibirsk, 1979). (P. L. Dreike et al.)
6. "Field Reversed Ion Layers", to appear in Proc. IAEA VIII Int'l. Plasma Physics and Controlled Nuclear Fusion Research Conf. (Brussels, Belgium, 1980). (P. L. Dreike, et al.)

Project

High Current Ion Source

D. S. Prono, R. J. Briggs

FY 79	\$ 200K op.	FY 80	\$ OK op.
	\$ 200K eq.		\$ OK eq.

Purpose

Our purpose was to research the new technology of "ion diode" and develop the technology along lines compatible to existing mirror machine requirements. The application is to use an intense pulsed ion source to assist in the creation and/or rapid heating of a field reversed plasma entity. Both applications serve to reduce the requirements of existing mirror machine neutral beam sources. An additional goal was to demonstrate that an intense pulsed ion beam could successfully cross a magnetic field by establishing an electric polarization field and that trapping of this beam would be accomplished by shorting out the polarization field by a target plasma. If successful, this would be an alternative to negative ion systems which also deliver very high kinetic energy ions (> 100 's of keV) to a plasma but have inherent inefficiencies in generation and trapping.

Approach

Our research program was to develop a pulsed reflex diode ion source system capable of generating and transporting ~ 1 kJ of D^+ ions at 100 keV in $1 \mu s$. The 1 microsecond pulse time is necessary to enable smooth filling of the field reversed target plasma (pulse time ~ 6 times the ion cyclotron time) and the 100 keV energy matches the 6kG field capability of LLNL's Beta II experiment. Transport of the ion beam is accomplished by using a plasma guide channel which develops a focusing net current.

Progress

We were able to generate and transport up to 1.3 kJ of 100 keV D^+ to a target 2.8 meters distant and with a pulse duration of 0.8 microseconds. The limit on the pulse time ($> 1 \mu s$ was our goal) is believed to be inherent to our type of device and does pose serious restrictions for future extrapolations. However, these operational parameters are still more than sufficient for meaningful experiments to be carried out on the Beta II facility. Because of the successful achievement of these operational parameters, the ion diode facility was installed in the Beta II experimental site and made operational there.

Plans

Resuming experiments with the ion diode facility in the Beta II experiment are awaiting development of the plasma gun field reversed target plasma. When this field reversed target plasma is achieved in the center cell of Beta II and if it requires additional pulsed heating then our experiments on cross field injection, trapping and target plasma response will commence.

Milestones

None

Graduate Students

None

Graduates

None

Other Professional Staff

None

Major Recent Publications

1. "Charge-Exchange Neutral Atom Filling of Ion Diodes: Its Effect on Diode Performance and A-K Shorting" D. S. Prono et al., UCRL-84438 submitted to Journal of Applied Physics.
2. "Generation, Extraction and Transport Operations Characteristics of a Reflex Ion Diode System" D. S. Prono et al., (in preparation).

Project
FRX-C

R. K. Linford, R. E. Siemon

FY 79	\$ OK op.	FY 80	\$1500K op.
	\$ OK eq.		\$ 175K eq.

Purpose

To improve the confinement properties of elongated prolate compact toroids containing purely poloidal (no toroidal) magnetic field by scaling from previous experiments to larger size and higher temperature.

Approach

Previous LASL FRX-A and FRX-B experiments have demonstrated that MHD stable compact toroids can be formed with a field-reversed theta pinch. By doubling the size and voltage in the FRX-C experiment (40-cm diameter, 2-m length, 100 kV), it will be possible to establish how much the confinement improves with the size scaling parameter S defined as R/ρ_1 where R is the major radius of the torus and ρ_1 is the ion gyro radius defined with respect to average temperature and external magnetic field. Because the FRX-C device is located at one end of the LASL compact toroid trapping facility (CTX), it will be possible to test translation and trapping of toroids in the quasi-steady magnetic fields of CTX.

Progress

1. The FRX-A and FRX-B experiments (coils with 22-cm diameter, 1-m length) have demonstrated the formation of stable compact toroids with typical particle confinement times of 40 μ s.
2. It has been observed on FRX-B by variations of fill pressure that the particle confinement time increases with $S = R/\rho_1$.
3. An $n=2$ rotational instability is observed to terminate the plasma confinement phase. The instability is predicted theoretically to occur after substantial particle losses (> 0.5), and experimental observations agree with this prediction.
4. The electron density and temperature measured by Thomson scattering combined with excluded flux measurements and spectroscopic ion temperature measurements show a plasma pressure profile consistent with the requirements of equilibrium in an elongated toroid, $\langle \beta \rangle = 1 - 0.5 x_s^2$ where $\langle \beta \rangle$ is the volume averaged β and x_s is the ratio of the separatrix radius to the metal coil radius.
5. Formation phase scaling laws based on FRX-B data have been used to predict parameters in FRX-C. For initial pressures of 10-40 mTorr the predicted total temperature ($T_e + T_i$) ranges from 1.5 keV to 0.5 keV, and larger values of S (approximately 20-40) can be expected as required to test the confinement scaling.

6. An improved preionization method capable of working at larger bias field (~ 4 kG) has been developed on FRX-A. It consists of an ionizing RF discharge (typically 70 MHz) followed by magnetoacoustic heating of the partially ionized gas to complete the ionization.

Plans

1. Operate FRX-B with larger capacitor bank to check scaling laws.
2. Operate FRX-B with larger bias field and with barrier fields to rest effect on trapped flux.
3. Study in greater detail both magnetoacoustic and axial current preionization methods.
4. Complete construction of FRX-C and implement diagnostics.

Milestones

1. Begin operation of modified FRX-B.	September 1980
2. Report results of modified FRX-B experiment.	January 1981
3. Complete construction and begin checkout of FRX-C experiment.	February 1981
4. Begin operation of FRX-C.	May 1981
5. Report initial results and examine need for FRX-C modifications such as axial current.	November 1981
6. Modify experiment to permit translation and trapping in CTX.	May 1982

Graduate Students

None

Graduates

None

Other Professional Staff

W. T. Armstrong, R. R. Bartsch, J. C. Cochran, R. J. Commisso, J. Lipson, K. F. McKenna, D. A. Platts, E. G. Sherwood, M. Tuszewski

Major Recent Publications

1. "Field Reversed Experiments (FRX) on Compact Toroids," W. T. Armstrong, R. K. Linford, J. Lipson, D. A. Platts, and E. G. Sherwood (submitted to Phys. Fluids).
2. "Compact Toroid Experiments and Theory," W. T. Armstrong, D. C. Barnes, R. R. Bartsch, R. J. Comisso, C. A. Ekdahl, I. Henins, D. W. Hewett, H. W. Hoida, T. R. Jarboe, C. G. Lilliequist, R. K. Linford, J. Lipson, J. Marshall, K. F. McKenna, J. P. Mondt, D. A. Platts, C. E. Seyler, A. R. Sherwood, R. E. Siemon, M. G. Tuszewski, D. V. Anderson, R. Christian, E. H. Klevans, S. Hamasaki, D. D. Schnack, J. M. Sayer, A. I. Shestakov, and J. Kilean, in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 8th Int. Conf. Brussels, 1980), to be published.

Project
CTX

R. K. Linford, A. R. Sherwood

FY 1979	\$1,700K op.	FY 1980	\$2,156K op.
	\$ 265K eq.		\$ 571K eq.

Purpose

In CTX we intend to investigate the production, equilibrium, stability and confinement properties of compact toroids (CT's) of the spheromak type (i.e., containing an internal toroidal field) in the absence of externally supported toroidal fields. These investigations will serve as input to evaluation of these configurations with respect to their potential advantages as reactor confinement systems.

Approach

The CTX system provides a trapping facility for spheromak-type CT's produced by a magnetized coaxial source and for FRC-type CT's that will be produced by the FRX-C source. The CTX facility has a 4.5-m long, 1.5-m diameter vacuum chamber fitted with DC coils capable of providing a 10-kG uniform magnetic field. Two hundred forty kilojoules of fast capacitor bank energy and 1 MJ of slow bank energy are available for the coaxial source and auxiliary pulsed magnetic field coils. The method of producing CT's using a magnetized coaxial source was tested and proved successful on the Prototype Gun Facility. Subsequently a magnetized source was installed on the CTX facility. The initial experiments are focusing on the production and stability of CT's trapped in various combinations of flux conserver geometries and magnetic guide fields. Later experiments will address questions such as impurity levels and transport processes.

Progress

1. The CTX facility was constructed in the area previously occupied by the Staged Theta Pinch. The facility has been made operational, and the initial investigations of CT's produced by a magnetized coaxial source and trapped in CTX are underway.
2. The method of producing spheromak-type CT's using a magnetized coaxial source has been demonstrated to work. Magnetic field reconnection leading to the formation of a CT separated from the source has been observed. (The e-folding times for reconnection are in the 10-15 μ s range)
3. A gross instability, the tilting mode, was observed when a prolate CT is trapped in a straight cylindrical flux conserver. Even so, lifetimes of 50-100 μ s for the > 70 eV, 10^{14} cm⁻³ plasma were observed.
4. CT's stable to the tilting mode have been produced in various combinations of magnetic guide field and oblate-shaped geometries for the flux conserver. Lifetimes of 100-200 μ s were observed.

Plans

1. Further investigate the production, stability and trapping of CT's in flux conservers having oblate geometries.
2. Install more detailed diagnostics and study the equilibrium and confinement of the trapped tori with and without guide fields of various geometries (e.g., uniform field, mirror fields, etc.).
3. Investigate the snipper coil technique of shortening the magnetic field reconnection time. Determine the effect of shortening this time on the plasma parameters and the CT's lifetime.

Milestones

1. New DC power supply to be tested and connected to CTX. November 1980
2. Report on trapping studies in CTX of spheromak-type CT's. November 1980
3. Report on physics studies of the properties of trapped spheromak-type CT's. September 1981
4. Prepare CTX for first injection of FRC-type CT's from FRX-C. May 1982

Graduate Students

None

Graduates

None

Other Professional Staff

I. Henins, H. W. Hoida, T. R. Jarboe, P. L. Klingner, J. Marshall.

Major Recent Publications

T. R. Jarboe, I. Henins, H. W. Hoida, J. Marshall, and A. R. Sherwood, "Magnetized Gun Experiments," Proceedings of the U.S. Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, December 12-14, 1979, Princeton, N.J.

R. K. Linford and CT staff, "The LASL Compact Torus Program," Proceedings of the U.S. Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, December 12-14, 1979, Princeton, N.J.

T. R. Jarboe et al., "The Motion of a Compact Toroid Inside a Cylindrical Flux Conserver," submitted to Phys. Rev. Lett. for publication.

T. R. Jarboe et al., "Production of Field-Reversed Configurations with a Magnetized Coaxial Plasma Gun," International Symposium on Physics in Open Ended Fusion Systems, April 15-18, 1980, Tsukuba, Japan.

W. T. Armstrong et al., "Compact Toroid Experiments and Theory," IAEA Eighth Int. Conf. on Plasma Physics and Cont. Nuclear Fusion Research, Brussels, Belgium, July 1-10, 1980.

Project

Experimental Program Based on a High-Beta Q Machine

F. L. Ribe

FY 79	\$ 200K op.	FY 80	\$ 188K op.
	\$ 28K eq.		25K eq.

Purpose

To investigate auxiliary radio frequency heating of high-beta plasmas near the magnetosonic and ion-cyclotron frequencies. To investigate formation of multiple field-reversed cells.

Approach

An experimental 3-m long, 22-cm bore staged theta pinch provides plasma with collisionless ions for end-confinement times in excess of the e-folding time for the r-f heating. R-f heating is applied in a wave structure of length comparable to that of the plasma. It is proposed to control particle and flow by application of multiple field-reversed cells produced by applying a periodically reversing bias field.

Progress

In the first year the HBQM has been constructed with main bank and passive crowbar. First plasma was produced in May 1979. In the second year (through July 1980) a plasma was produced with improved crowbar ripple and diagnosed by end-on holography and excluded flux measurements. The periodic collector plates were delivered. Theory was worked out for faster and slow-wave ion Landau damping and ICRH.

Plans

During the second year studies were initiated to determine the characteristics of the plasma and the r-f heating system. During the third year results will be obtained on r-f heating and multiple field-reversed cells.

Milestones

1. Operate preionization and make initial plasma measurements. May 1979
2. Operate main bank, passively crowbarred, with plasma diagnostics. February 1980
3. Improve passive crowbar. July 1980
4. Install periodic collector plates and r-f capacitors. October 1980

5. Preliminary tests of formation of multiple field-reversed cells.

November 1980

6. R-f heating experiments on passively crowbarred plasma.

March 1981

7. Install power crowbar.

August 1981

Graduate Students (% DOE Support)

H. Meuth (100%)
E. Sevillano (100%)
K. Bych (40%)
R. Sanchez (60%)

Graduates

D. Zabloudil

Other Professional Staff

S. O. Knox, Research Assistant Professor
G. Harper, Technician

Major Recent Publications

1. "Finite-Wavelength Oscillation of a Diffuse-Profile, Vlasov-Fluid Plasma Column," R. Sanchez, University of Washington Report UWFPP, Revised (April 1980).
2. "Ion-Cyclotron Heating of a Vlasov-Fluid Theta-Pinch Plasma Column," R. Sanchez, University of Washington Report UWFPP-8 (March 1980).
3. "Periodic Field-Reversed Equilibria for a Multiple-Cell Linear Theta Pinch," H. Meuth and F. L. Ribe, Proc. U.S-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, N.J. (December 1979).
4. "Ion Cyclotron Heating of a Vlasov-Fluid Theta-Pinch Plasma Column," R. Sanchez and F. L. Ribe, Proc. Sherwood Theory Meeting, Tucson, AR (April 1980).,
5. "A Three-Meter Staged Theta Pinch with a Periodic Compression Coil Drive," S. O. Knox, H. Meuth, F. L. Ribe and E. Sevillano, IEEE International Conference on Plasma Science, Madison, WI (May 1980).
6. "The Construction and Characterization of Marx Pulse Generators," D. W. Zabloudil, M. S. Thesis, University of Washington (1980).

Project

Field Reversed Plasma Gun Experiment

W. C. Turner

FY 79	\$1500K op.	FY 80	\$ OK op.
	\$ OK eq.		\$ OK eq.

Purpose

Use a magnetized co-axial plasma gun to produce field reversed plasma rings which may be injected into and trapped in a magnetic mirror. The ultimate goal would be to further heat and sustain the field reversed plasma with neutral beam injection.

Funds for this project are provided for construction of the plasma gun to be used on the Beta II device at Livermore. After completion of construction (August 79) the experimental operation is funded by the Confinement Systems Branch.

Approach

A coaxial plasma gun is fitted with solenoids which, together with an external guide field, produce a magnetic cusp at the gun muzzle. Plasma accelerated through the cusp region carries the flux of the inner electrode with it because of magnetic induction. This causes elongation of field lines emanating from the inner electrode and reversal of the magnetic field downstream of the gun. The axially elongated (poloidal) field lines reconnect behind the emerging plasma to produce a closed field line toroidal configuration. Accelerating B_θ field originally between the gun electrodes is trapped in the moving plasma and provides a toroidal field component in the plasmoid.

Progress (through 7/80)

1. A field reversed plasma gun has been designed. The parameters chosen include an inner electrode diameter of 15 cm, an outer electrode diameter of 30 cm, a length of 150 cm, an inner solenoid of 133 turns which produces a field of ~ 40 kG, and an outer solenoid of 133 turns which produces a field of ~ 6 kG. The guide field is ~ 6 kG.
2. The inner electrode and solenoid have been fabricated and assembled. The outer electrode and solenoid have been fabricated and assembled. The gas valve has been assembled. The collector plates and gun support have been designed and are being fabricated.

3. The main gun bank (40 kV, 185 kJ) has been designed, fabricated, and is being assembled. The inner electrode solenoid bank (4 kV, 690 kJ) and outer solenoid bank (4 kV, 60 kJ) have been designed and are being fabricated. The power supplies are being installed.
4. The plasma gun experiment control systems have been designed, and are being fabricated and installed.
5. Detailed calculations and parameter studies have been made of expected gun behavior, using MHD codes. Conditions for reconnection of the field lines have been predicted using a 2D code.
6. The plasma gun has been designed to be used with and diagnosed with the Beta II magnetic mirror facility.
7. The plasma gun has been shown to successfully produce field reversed plasma. Reconnection of poloidal field lines did not occur. The cause was identified as slow plasma flowing from the gun, keeping the field lines open until they receded back to the gun instead of allowing formation of a closed field line of plasmoid.
8. The geometry of the gun electrodes and the pulsed gas valve have been redesigned to allow reconnection of the poloidal field lines. A pulsed pinching coil to force reconnection has also been designed.
9. Construction of the new gun electrodes and gas valve have been completed, assembly and initial testing are underway.

Plans

1. Demonstrate formation of field reversed plasma with closed poloidal field lines.
2. Demonstrate MHD stable plasma confinement.
3. Achieve formation of field reversed plasma with density, lifetime and poloidal flux suitable for a neutral beam injection target plasma.
4. Heat and sustain field reversed plasma with neutral beam injection.

Milestones

1	Checkout capacitor banks for plasma gun.	June 1979
2.	Begin field reversed plasma gun experiments.	August 1979
3.	Complete Beta II stand-alone facility.	September 1979

4. Generate field reversed plasma rings.	December 1979
5. Submit report on generating field reversed plasma rings.	February 1980
6. Begin plasma ring injection and trapping experiments.	March 1980
7. Trap field reversed plasma rings in Beta II.	June 1980
8. Submit report on injection and trapping of field reversed plasma rings.	July 1980
9. Begin operation of plasma gun with electrodes and gas valve modified for reconnection of poloidal field.	September 1980

Graduate Students

None

Graduates

None

Other Professional Staff

C. W. Hartman, D. S. Prono, J. Taska, H. Bell, M. Calderon,
A. K. Chargin, R. Rubert

Major Recent Publications

1. J. L. Eddleman, C. W. Hartman, J. W. Shearer, "MHD Calculations of Field Reversed Plasma Ring Formation", Bull. Am. Phys. Soc. 23, 7 (1978) Paper 6Q12.
2. C. W. Hartman, J. W. Shearer, T. C. Simonen, and W. C. Turner, "Applications of Field-Reversed Plasma Rings" Bull. Am. Phys. Soc. 23, 7 (1978) Paper 6Q13.
3. J. W. Shearer, J. L. Eddleman, C. W. Hartman, W. C. Turner, "Numerical Calculations of Plasma Gun Operation and Formation of Field Reversed Plasma", Paper 3E4 6th IEEE International Conference on Plasma Science, Montreal, June 4-6, 1979.
4. C. W. Hartman, G. A. Carlson, W. S. Neef and A. C. Smith, Jr., "Design Studies of an FRM Pilot Reactor Start-Up Using a High Energy Coaxial Plasma Gun." Paper 3E7 6th IEEE International Conference on Plasma Science, Montreal, June 4-6, 1979.
5. W. C. Turner, C. W. Hartman, J. W. Shearer, J. Taska, "Field Reversed Plasma Gun Experiment", Bull. Am. Phys. Soc., 24, 1083, 1979.

6. J. L. Eddleman, C. W. Hartman, J. W. Shearer, W. C. Turner, "Magnetohydrodynamic Calculations of Coaxial Gun Production of Plasma", Bull. Am. Phys. Soc., 24, 1083, 1979.
7. J. W. Shearer, J. L. Eddleman, C. W. Hartman, W. C. Turner, "Field Line Reconnection in Coaxial Gun Produced Plasma", Bull. Am. Phys. Soc., 24, 1083, 1979.
8. W. C. Turner, C. W. Hartman, J. Taska, A. C. Smith, Jr., "Initial Results of Field Reversed Plasma Gun Experiment", UCRL-83687. Submitted to U.S.-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection", Princeton Plasma Physics Laboratory, December 12-14, 1979.
9. C. W. Hartman, W. C. Condit, E. H. A. Granneman, D. S. Prono, A. C. Smith, Jr., J. Taska, W. C. Turner, "Field Reversal Produced by a Plasma Gun", UCRL-84228. Submitted to International Symposium on Physics and Open-Ended Fusion Systems", Tsukuba, Japan, April 15-18, 1980.
10. W. C. Turner, E. H. A. Granneman, C. W. Hartman, D. S. Prono, J. Taska, A. C. Smith, Jr., "Production of Field-Reversed Plasma with a Magnetized Coaxial Plasma Gun", UCRL-84294, April 23, 1980 submitted to Journal of Applied Physics.
11. W. C. Turner, E. H. A. Granneman, C. W. Hartman, D. S. Prono, J. Taska, A. C. Smith, Jr., "Studies of the Formation of Field Reversed Plasma by Magnetized Co-Axial Plasma Gun", UCRL-84450. Submitted to Reversed Field Pinch Theory Workshop, Los Alamos Scientific Laboratory, April 28-May 2, 1980.
12. W. C. Turner, W. C. Condit, E. H. A. Granneman, C. W. Hartman, D. S. Prono, A. C. Smith, Jr., J. Taska, "Field Reversed Plasma Gun Experiment", 1980 IEEE International Conference on Plasma Science, May 19-21, 1980, Madison, Wisconsin.
13. J. L. Eddleman, J. W. Shearer, W. C. Turner, "Numerical Calculations of the Beta-II Field Reversal Experiment", 1980 IEEE International Conference on Plasma Science, May 19-21, 1980, Madison, Wisconsin.
14. J. W. Shearer, W. C. Condit, W. C. Turner, "Some Scaling Relationships for Field-Reversed Mirror Experiments", 1980 IEEE International Conference on Plasma Science, May 19-21, 1980, Madison, Wisconsin.

Project

Investigation of Compact Toroid Physics

G. C. Vlasses, Z. A. Pietrzyk

FY 79	\$ 180K op.	FY 80	\$ 207K op.
	\$ 56K eq.		\$ 20K eq.

Purposes

1. To study field reversed θ -pinch-like configurations at high density, using CO_2 laser auxiliary heating, in order to reach high values of a/ρ_1 .
2. To study the compression of magnetized, wall-contact plasmas by an imploding metal shell.
3. To provide analytical and computational support for the experimental program and novel advanced fusion concepts.
4. To conclude work on material end plugging of linear devices.

Approaches

There are two principal experimental devices. The first is a "fast solenoid" or multi-turn θ -pinch which uses μsec pulses of up to 1 kJ, for supplemental heating to attain conditions in the range of $T \sim 80 \text{ eV}$, $n \sim 3 \times 10^{17}$, $\beta \sim 1$. The second is an imploding liner apparatus with a 10 kV, 100 kJ capacitor bank which accelerates aluminum shells, similar in dimensions to soft drink cans, to velocities of 2-3 mm/ μsec . Laboratory diagnostic capabilities include Thomson scattering systems, holography, fast photography, spectroscopy, diamagnetic loops, and flash X-rays. The computational effort makes use of an RJET link to the MFE computer at Livermore.

Progress: Oct. 1979 - September 1980

1. Completion of the imploding shell device, with design goals achieved.
2. Installation of reverse bias bank on fast solenoid.
3. Design and construction of new magnet for field reversal experiment.
4. Initiation of Thomson scattering measurements on fast solenoid.

5. Extensive 2-D modelling of reverse field θ -pinches, with controlled reconnection and with/without supplemental heating.
6. Completion of analytical studies relating to cusp-ended solenoid and ablating liner reactors.
7. Completion of study of parallel heat conduction with arbitrary collisionality (λ/d).

Plans

1. Completion of preionization studies for field reversal experiment.
2. Installation of new magnet for field reversal experiment.
3. Large α ruby scattering measurements for the field reversal experiment.
4. Completion of testing initial plasma system(s) for imploding liner.
5. Development of long wavelength scattering diagnostics for application to University of Washington High Beta Q Machine (see page 30).
6. Further 2-D modelling of field reversal experiments.

Milestones

1. Initial firing of imploding shell device, January 1980. (Achieved)
2. Installation of Thomson scattering apparatus on fast solenoid, June 1980. (Achieved)
3. X-ray and magnetic probe measurements of liner performance, Summer 1980. (Achieved)
4. First firing of shell onto plasma load, Winter 1981.
5. Initial operation of field reversal experiment with new magnet and preionization system, Winter 1981.

Graduate Students (% DOE Support)

R. Carson (100), T. Carlstrom (100), K. Wira (100), K. Kawai (100).
P. Trinh (50), M. Shirazian (20).

Graduate - Ph.D. (Cumulative)

N. Amherd (73), J. Pearlman (74), H. Rutkowski (75), H. Willenberg (76),
R. Massey (76), H. Hoida (78), D. Scudder (79), R. Brooks (79), R. Watt (79)
M. Shirazian (80), W. Terry (80).

Other Professional Staff

Professor A. Hertzberg (5%)
R. Marrs, Research Asst. Professor (100%)
D. Lotz, Research Engineer (75%)

Major Recent Publications

"Energy Confinement Considerations For Two Advanced Fusion Linear Reactor Concepts," William K. Terry, Ph.D. Thesis, University of Washington, 1978.

"Raman Backscattering From Underdense Plasma Columns," R. G. Watt, Ph.D. Thesis, University of Washington, 1979.

"Parallel Heat Conduction in Plasmas Between Flat Plates For Arbitrary Mean Free Path," Mohammed Shirazian, Ph.D. Thesis, University of Washington, 1980.

"Thomson Scattering From An Anisotropic Plasma," R. G. Watt & Z. A. Pietrzyk, Phys. Fluids 22, 778 (1979).

"Two-dimensional Lagrangian Calculation Of A Laser-Heated Solenoid," A. H. Makomaski & Z. A. Pietrzyk, Phys. Fluids 23, 379 (1980).

"Observation Of Stimulated Brillouin Backscatter Saturation in an Underdense Plasma for a Long CO₂ Laser Pulse," Z. A. Pietrzyk & T. N. Carlstrom, Appl. Phys. Letters 35, 681 (1979).

"Multiple-Pass Laser Heating of a Short Plasma Column," R. D. Brooks, Z. A. Pietrzyk & G. C. Vlases, J. of Physique 40:C7, 751, (1979).

Project

Spheromak (S-1) Fabrication

J. C. Sinnis

FY 80 \$ 800K op.

 \$ OK eq.

Purpose

To generate a spheromak plasma by using quasi-static inductive forming techniques so as to minimize peak power requirements and plasma electrode contact. The reactor advantages of the Spheromak are its large engineering beta value and the fact that the coils and blanket do not topologically link the plasma.

Approach

The S-1 device will generate the toroidal and poloidal plasma currents required to create an equilibrium configuration by employing inductive forming techniques. The salient features of the device include a spheroidal vacuum vessel containing a one meter major radius, 20 cm minor radius toroidal flux core. Within the flux core are the toroidal flux (TF) and poloidal flux (PF) windings whose time varying fields, induce the plasma currents.

During the early stage of the formation process these plasma currents flow in an annular region surrounding the flux core. As the formation proceeds in time a "private flux" region forms on the small major radius side of the flux core and the plasma separates away from the core. This spheromak plasma moves inward to a radius determined by the current level in the Equilibrium Field (EF) coil system. In addition to providing the vertical field required for radial equilibrium of the spheromak plasma, the field index of the EF circuit determines the plasma shape, negative field indices giving rise to prolate spheromaks and positive indices yielding oblate spheromaks. The S-1 EF coil system has the flexibility to change the field index from $-0.03 < n < +0.35$ in discrete steps.

Progress

1. The S-1 proposal was reviewed in Germantown, Maryland on September 6, 1979 and authorization to proceed with fabrication was received in a letter dated January 4, 1980.
2. Magnetic design studies and resistive MHD code calculations were completed during the past year. These studies result in a variable field index design and the elimination of the "pinching" coils.
3. Components and materials ordered and delivered include the vacuum vessel domes, copper for the EF coils and Inconel for the flux core line.

Plans

The next phase of the fabrication program will concentrate on the design and procurement of the flux core. This toroidal assembly consists of a fiber reinforced core fabricated from discs of G-10 material. Grooves machined in the core provide channels for the PF and TF windings and the core, together with its armature banding tape overwrap, support the conductors against magnetic loads. The flux core assembly is encased in a thin vacuum tight inconel jacket (liner) to prevent outgassing of the insulating materials. Electrical components on order and scheduled for early FY81 delivery include the energy storage capacitor banks for the TF and PF circuits (1 MJoule total) and the ignitron switching tubes. Fiscal '81 fabrication activity will include: 1) machining and welding of the vacuum vessel diagnostic ports and main flanges, 2) Completion of the area clean up and initiation of the capacitor bank and switch tube installation, 3) Winding of the vertical field coils.

Milestones

1. Vacuum Vessel Design Complete.	December 1980
2. Flux Core Case Design Complete.	February 1981
3. TC Winding Fabrication Complete.	November 1981
4. EF Coil Fabrication Complete.	December 1981
5. Area Preparation Complete.	January 1982
6. Vacuum Vessel Fabrication Complete.	January 1982
7. Ignitron Switching Complete.	January 1982
8. PC/TC Capacitor Banks Ready.	April 1982
9. Flux Core Fabrication Complete.	May 1982
10. Electrical System Cable/Bus Ready.	July 1982
11. Leak Check Vacuum Vessel.	September 1982
12. Operating Controls Ready.	October 1982
13. Individual Coil Systems Power Tests.	November 1982
14. First Plasma.	December 1982

Graduate Students

None

Graduates

None

Major Recent Publications

(New Project)

Project

Spheromak Research (S-1 Op.)

M. Yamada

FY 79	\$ 200K op.	FY 80	\$ 700K op.
	\$. OK eq.		\$ 50K eq.

Purpose

1. Generate a spheromak configuration by a slow "quasi-static" formation scheme, suitable for future scale-up to a reactor size.
2. Investigate the MHD stability and the energy confinement properties of the spheromak configuration.

Approach

The proposed S-1 scheme creates a spheromak plasma configuration without using a coil which links the compact toroidal shape plasma. In this scheme, a toroidal shape flux core containing a time-varying toroidal flux inside and generating a L=1 Levitron type poloidal field configuration, generates a plasma current in both toroidal and poloidal direction by inductive mechanism. After the plasma is expanded toward the major axis, it is pinched off from the topology linked with the flux core.

The device is relatively large (plasma major radius of 50 cm, minor radius of 25 cm) and has weak magnetic field ($B_{t0} \leq 9$ kG). Nonetheless, the toroidal plasma current of 500 kA is sufficient to produce electron temperatures of the order of 100 eV. Furthermore, a relativistic electron beam can be injected into the outer region of the plasma through a plasma anode gun to heat the plasma.

When appropriate formation and heating techniques have been demonstrated, we will proceed in Phase 2 to the 'Proof of Principle Experiment' of the spheromak configuration. If the results of the Phase 2 are encouraging, we will proceed to the Phase 3, ignition device.

Progress

1. Final engineering design of the S-1 facilities has been completed. An improved and complete magnetic design of the S-1 flux core system has been undertaken resulting in better control of poloidal field configuration.
2. Recently a proto-type S-1 device (called Proto S-1A) has been built and has successfully created a spheromak configuration, demonstrating the effectiveness of the S-1 formation scheme. Upon this success, the fast data acquisition system for the proto-S-1 experiment has been constructed using Camac 4 MHz digitalizers and memory units.

3. An extensive computer simulation by a resistive MHD code, has been carried out to study the S-1 formation scheme, contributing significantly to the engineering design of the S-1 device.

Plans

1. During FY 81, the proto S-1 experiment will be intensively continued to thoroughly investigate the S-1 spheromak formation processes. Furthermore, the transport phenomena of the spheromak configuration will be studied by monitoring density (CO_2 interferometry) and temperature (Thomson scattering).
2. The initial design of the S-1 diagnostic system such as laser-Thomson-scattering system, UV spectroscopy of residual gas analyzer are started. The proto-type systems for these diagnostics will be tested in the proto S-1 apparatus.
3. Theoretical studies of the MHD stability characteristics of the spheromak configuration will be carried out by using a resistive MHD code and the PEST codes.

Milestones

1. Start proto S-1 experiments.	April 1980
2. Complete phase 1 theoretical analysis of the S-1 formation scheme.	September 1980
3. Begin phase 2 of proto S-1 experiments
$R_p = 12 \text{ cm}$, $a_p \sim 8 \text{ cm}$, $T_e \sim 30 \text{ eV}$.	October 1980
4. Start preparation diagnostics and data acquisition for S-1 device.	October 1980
5. Complete proto S-1 experiments.	September 1982
6. Start S-1 operations.	December 1982

Graduate Students

W. Hsu (100%)
W. Heidbrink (100%)

Major Recent Publications

1. M. Okabayashi and A. M. Todd, Nucl. Fusion 20 571 (1980).
2. H. Furth, Proc. of U.S.-Japan Symp. on Compact Toroids, Dec. (1979) PPPL, P.1; M. Yamada, et al., ibid p. 171; M. Okabayashi et al., ibid p. 166; T. Stix and A. Todd, ibid p. 204; M. Katsurai and M. Yamada, ibid p. 212.
3. W. Grossmann et al., Proc. of 8th IAEA Conf., Brussels, 1980 IAEA-CN-38-R-1.
4. M. Yamada et al., to be submitted to Phys. Rev. Lett.

Project

Spheromak

G. C. Goldenbaum, A. W. DeSilva

FY 79	\$ 25.6K op.	FY 80	\$ 230K op.
	\$ 34.4K eq.		\$ 50K eq.

Purpose

To establish means for producing a spheromak configuration and to study the properties of the spheromak configuration.

Approach

Fast capacitor bank discharges are used to induce the currents and fields for the spheromak configuration. Two approaches are being investigated: PS-1 uses a combined zee and theta pinch technique and SPS involves ionizing shock waves launched toward each other from two ends of a solenoidal guide field.

Progress

Formation of the required closed flux surfaces and paramagnetic toroidal field has been observed in PS-1. No instabilities have occurred so far. SPS has been constructed and operating conditions are being surveyed.

Plans

Longer pulse length applied fields (3 msec) will be used on PS-1 to study long time effects. A larger, more collisionless, extension of the PS or SPS experiment is being planned.

Milestones

1. Install new long pulse bank and coil on PS.	March 1980
2. Evaluate possibilities for long pulse length, high temperature, large diameter experiment.	April 1980
3. Evaluate formation of spheromak configuration in SPS.	March 1981

Graduate Student

G. Hart (100%)

Graduates

None

Other Professional Staff

Y. P. Chong, Research Associate
J. H. Irby, Research Associate
C. Chin-Fatt, Research Associate

Major Recent Publications

1. "Formation Of A Spheromak Plasma Configuration", G. C. Goldenbaum, J. H. Irby, Y. P. Chong, G. W. Hart (submitted for publication).
2. "Paramagnetic Spheromak Formation In A Combined Zee and Theta Pinch," G. C. Goldenbaum, J. H. Irby, Y. P. Chong, G. W. Hart, Proceedings of the 9th European Conference on Controlled Fusion and Plasma Physics, Oxford, 1979.
3. "Dynamically Formed Spheromak Plasmas (PS-1)", G. C. Goldenbaum, Y. P. Chong, J. H. Irby and G. W. Hart, Proceeding of the U.S.-Japan Symposium on Compact Toruses and Energetic Particle Injection, Princeton, 1979.
4. "Generation of a Spheromak Configuration by Pulse Techniques," A. W. DeSilva, Proceeding of the U.S.-Japan Symposium on Compact Toruses and Energetic Particle Injection, Princeton, 1979.

Project

Compact Torus Research

A. Fisher, S. Robertson and N. Rostoker

FY 79	\$ 136K op.	FY 80	\$ 150K op.
	\$ 7K eq.		\$ 0K eq.

Purpose

To investigate the initiating and sustaining of compact toroidal plasma discharges by means of energetic particle beams.

Approach

1. Field-reversed configurations are produced by (1) plasma return currents induced by a short pulse (1 MV, 0.1 MA, 50 ns) electron beam fired into 200 mT H₂ gas, and (2) a long pulse electron beam (0.6 MV, 20 kA, 0.6 - 1 μsec) fired into H plasma at 10¹² - 10¹³ cm³. Induced fields of order 2 kG are created for up to 15 μsec (case 1) and 1 μsec (case 2) in chambers 20 cm dia. x 50-150 cm long.
2. An intense pulsed ion beam (100 kV, 1 kA, 0.6 μsec) is radially incident upon an 0-6 kG toroidal magnetic field. Intense longitudinal and transverse electric fields are generated which drift part of the beam 2-4 Larmor radii into the field.

Progress

1. Production of two consecutive pulses 2 msec apart from an ion diode and extraction of deuterons in an intense beam from a Ti washer source.
2. Theoretical description of the interaction of a charge-neutral ion beam with a magnetic barrier with one-dimensional, time dependent, relativistic and diamagnetic model.
3. Observation that a tokamak discharge is not disrupted when an intense ion beam is fired into it.
4. Creation of a closed field reversed magnetic configuration by return currents induced by an electron beam launched through a half-cusp. Lifetimes of 4 - 15 μsec are observed and detailed magnetic profiles have been obtained.
5. Generation of field reversal in plasma by a transient e-layer generated by an electron beam fired through a cusp.

6. Reflection of e-layer by a magnetic mirror field.
7. Upgrade of ion diode from 1 kA to 3 kA.

Plans

1. Construction and installation of tangential ion injection port on the UCI tokamak.
2. Completion of two-dimensional, time dependent model of cross-field ion beam propagation.
3. The design of an experiment to inject electrons into the UCI tokamak using existing generators.
4. Addition of toroidal field (z-discharge) to the Long Pulse E-beam CT experiment.
5. To increase the magnetic Reynolds number in the short-pulse E-beam CT experiment.

Milestones

1. Complete modification to OH and VF coils to allow tangential injection.	August 1980
2. Complete 2-d time dependent model of cross-field propagation.	August 1980
3. Magnetic field measurements in reconnection region of Long Pulse E-beam CT experiment.	September 1980
4. Install tangential injection port on UCI Tokamak.	November 1980
5. Replace neutral gas-by plasma in short pulse E-beam CT experiment.	December 1980
6. Measure ion trapping in toroidal field.	January 1981

Graduate Students

G. Saenz (100%) W. Peter (100%)

Graduates

K. Molvig (1975), T. Tajima (1975), H. Tahsiri (1976), F. Wessel (1980).

Other Professional Staff

H. Ishizuka, A. Ron

Major Recent Publications

1. Multichannel Neutral Atom Energy Spectrometer for Plasma Diagnostics, S. Robertson, P. Korn, F. Sandel, and M. Greenspan, I.E.E.E. Trans. Plasma Sci. PS-7, 131 (1979).
2. Feedback Stabilized Fractional Fringe Laser Interferometer for Plasma Density Measurements, John Schneider and S. Robertson, Rev. Sci. Instrum. 50, 856 (1979).
3. Microsecond Pulsed Ion Beam from a Marx Generator, S. Robertson and M. Wickham, I.E.E.E. Trans. Plasma Sci. PS-7, 62 (1979).
4. Consecutive Microsecond Pulsed Ion Beams from a Reflex Tetrode Ion Source, S. Robertson, and F. Wessel, Appl. Phys. Lett 34, 7 (1979).
5. An Intense Pulsed Magnetically Insulated Deuteron Source, G. Endo and S. Robertson, Appl. Phys. Lett. 35, 849 (1979).
6. Propagation of a Wide Ion Beam into a Magnetic Barrier, W. Peter, A. Ron, and Norman Rostoker, Phys. Fluids 22, 1471 (1979).
7. E-Beam Heating of a Mirror Confined Plasma, S. Robertson, A. Fisher and C. Roberson, Phys. Fluids 23, 322 (1980).
8. Plasma Heating by an Electron Beam from a Foilless Diode, S. Robertson and A. Fisher, J. Appl. Phys., to appear August 1980.
9. Virtual Anode Formation by an Intense Pulsed Ion Beam Incident Upon A Transverse Magnetic Field, Scott Robertson and Frank Wessel, Appl. Phys. Lett., to appear July 15, 1980.

Project

Plasma Confinement by Megagauss Fields (LINUS)

E. P. Scannell

FY 79	\$ 200K op.	FY 80	\$ 200K op.
	\$ OK eq.		\$ OK eq.

Purpose

To demonstrate that the application of magnetic flux compression by liquid metal liners to the confinement and heating of high density plasma can lead to simple, compact, and economical fusion reactors.

Approach

Parameterization and diagnostic experiments will be conducted on LINUS-0 and HELIUS, in order to investigate magnetic flux compression by liners of sodium-potassium (NaK) eutectic liquid metal alloy, the hydrodynamics of such liners, and the operating characteristics of the machines, such data may be used to verify numerical calculations and thereby to extrapolate these to future LINUS plasma compression experiments and fusion reactor schemes.

Progress

1. Axisymmetric implosion systems have been developed in which the axial displacement of an annular free-piston causes the radial implosion of the inner surface of a rotating hollow liquid cylinder or liner.
2. Experiments with hydrodynamic models have demonstrated completely stabilized implosions in which a specularly reflecting inner surface is maintained during implosion and reexpansion. Up to thirteen cycles of implosion-reexpansion of the inner surface have been observed. Variations of the inner surface radius with axial position and time have been analyzed as a function of implosion chamber geometry.
3. Rotational stabilization of high frequency Rayleigh-Raylor modes on the inner surface has been examined in terms of the loss of surface reflectivity when the kinematic acceleration exceeds the centripetal acceleration. Excellent correlation of experiment and theory is obtained.
4. A high energy density implosion system called HELIUS has been designed, built and operated. The apparatus has been tested up to design maxima of rotation and drive pressure 3600 RPM and 200 PSI, and initial magnetic flux compression with NaK liners at low-to-medium drive pressures (500-1000 PSI) has been obtained. Implosions have been similar in quality to those in earlier axisymmetric implosion systems using water liners.

Normalized pressures of $\zeta = 0.015$ are indicated, which are a factor of ten greater than previously achieved with piston-driven liners, and begin to approach levels suitable for fusion feasibility experiments and economical reactions ($\zeta = 0.04-0.2$).

5. Helius has also been used to study axial loss of liner material through end ports during implosion.
6. Compressibility effects in stabilized liner implosion fusion systems have been analyzed by theoretical/numerical models to achieve scaling laws and system optimizations.
7. The LINUS-O high energy density 60 MJ implosion facility has been given a long series of shakedown runs, including some approaching its design limits of rotation and drive pressure. LINUS-O utilizes the high explosive gas driven piston technique to cause the implosion of a rotating hollow liquid liner, 15 cm long.
8. LINUS-O has been used to achieve high speed implosion of water liners with velocities greater than 120 meters/sec, with times to turnaround (i.e., minimum radius and maximum payload pressure) approaching 2 millisecc, close to reactor values.
9. Magnetic field maxima and flux diffusion calculated passively with respect to liner dynamics, with the drive pressure history as the only input, agreed very well with the above HELIUS NaK shots. Using this same passive flux diffusion technique, liner stability and machine operating parameter spaces were calculated and this was used to estimate maximum flux compression values achievable in both LINUS-O and HELIUS.

Plans

1. Operation of the LINUS-O and HELIUS implosion systems to study stabilized implosions at highest possible energy densities, in particular:
 - a) Basic dynamic behavior of piston-driven, rotating liquid liners compressing trapped-gas payloads at machine design limits.
 - b) Magnetic diffusion during implosion of sodium-potassium (NaK) liners onto trapped magnetic flux into the nonlinear regime, especially in LINUS-O.
 - c) Machine acoustic shock loadings due to internal pressure waves in the liner ("water hammer").
 - d) Initial studies of vaporization of the inner surface of a stabilized imploding liner.

The purpose of these experiments is to provide the quantitative base for extrapolation to higher energy liner systems needed for proof-of-principle and scientific feasibility experiments.

2. Conduct experiment on tangentially injected water liners (i.e., non-rotating reactor vessel).
3. More accurate maximum magnetic flux compression and diffusion into the nonlinear regime will be determined from self-consistent calculations; i.e., where the magnetic pressure interacts significantly with liner dynamics.

Milestones

1. Completion of experimental program on stabilized implosions
 - 1.a,b, and c (above). March 1981
 - 1.d, and 2 (above). September 1981
 - 3 (above). December 1980
2. Complete first design of LINUS plasma compression experiments. June 1981

Graduate Students

None

Graduates

None

Other Professional Staff

None

Major Recent Publications

1. P. J. Turchi, D. L. Book, R. Burton, and A. L. Cooper, "Stabilized Imploding Liner Research for High Magnetic Field Plasma Compression", (published in Journal of Magnetism and Magnetic Materials, 11, 372, (Amsterdam) (1979).
2. R. L. Burton and P. J. Turchi, "Compact Fusion Reactors Using Controlled Imploding Liners", Proc. 13th Intersociety Energy Conversion Engineering Conference, Paper 789224, San Diego, 1978.
3. D. L. Book and P. J. Turchi, NRL Memorandum Report 3699, "Numerical Studies of Compressibility Effects in Rotating Imploding Liquid Liners", January 1978.

4. P. J. Turchi, D. C. Book, and R. L. Burton, "Optimization of Stabilized Imploding Liner Fusion Reactors", Proc. 10th Symposium on Fusion Technology, September 4-8, 1978, Padova, Italy (N. Holland Press.).
5. R. A. Krakowski, et. al., "Reactor Systems Studies of Alternative Fusion Concepts", (to be published in Eighth International Conf. on Plasma Phys. and Controlled Nucl. Fusion Res., Brussels, Belgium, 1980).

Project

Field Reversed Configuration with Plasma Currents Induced by
Rotating E-Beams

J. Sethian

FY 79	\$ 77K op.	FY 80	\$ 50K op.
	\$200K eq.		\$ 0K eq.

Purpose

To study the formation, confinement, stability and long term behavior of a compact toroid generated with plasma currents induced by a rotating relativistic electron beam.

Approach(es)

Hollow rotating relativistic electron beams are injected into a cylindrical metal chamber containing neutral hydrogen. The beams break down the gas, heat the resulting plasma, and upon leaving the system, induce aximuthal and axial plasma currents that maintain the compact toroid configuration. There is no applied magnetic field, the radial equilibrium after beam termination is determined solely by the self fields of the induced plasma and wall currents.

Progress

1. In previous experiments, a single rotating relativistic electron beam (900 kV, 120 kA, 120 nsec) has been used to create a reversed field geometry with both axial (poloidal) and azimuthal (toroidal) fields. The fields were maintained for some 20 μ sec by the induced plasma currents. Electron temperature and density were 7 eV and $2 \times 10^{16} \text{ cm}^{-3}$, respectively.
2. A simple theoretical model has been formulated to describe the generation and propagation of the rotating beam. The beam equilibrium (radius and current pitch angle) is determined by conservation of canonical angular momentum, and flux, and the force balance between the fields produced by the beam; whereas the beam velocity is determined by the balance of power between the capabilities of the diode and the requirements of the induced fields. This model has been fully verified in the laboratory.

3. In the present state, a net axial current flows from one end of the system to the other and then returns through the drift tube wall. As this current is carried by the plasma, it represents a loss mechanism that precludes axial containment. For confinement, the axial current should return only in the plasma, rather than the tube wall; i.e. the axial current should close inside the plasma.
4. The current lines can be closed with a second counter-streaming electron beam. If this second beam, rotating in the same sense as the first, is injected between the first beam-produced plasma and the tube wall, it will amplify the initial axial fields, but will cancel out the initial axial current. The configuration would now be free to contract axially from the end walls without interrupting the axial current path, resulting in a compact toroid geometry. A second electron beam generator (1.6 MeV, 200 kA, 120 nsec) is being completed in order to test this concept.
5. The model described in (3) above has been extended to include a second beam. Calculations show that it takes comparatively little energy to rearrange the axial current path, and consequently the beam velocity is not reduced appreciably by the need to supply the self-fields.

Milestones

1. Complete new generator.	October 1980
2. Start experiments with new generator.	December 1980
3. Complete initial studies to close current lines.	June 1980
4. Complete studies to attain elevated plasma temperatures.	September 1980
5. Study possibility of post formation heating through magnetic compression.	September 1981

Grate Students (% DOE Support)

None

Graduates

None

Other Professional Staff

None

Major Recent Publications

1. "Generation of a Reversed Field Configuration without an Applied Magnetic Field", J. D. Sethian, K. A. Gerber, D. N. Spector, and A. E. Robson, Phys. Rev. Lett. 41, 798 (1978).
2. "The Use of Relativistic Electron Beams to Create Magnetically Controlled Plasmas Inside Imploding Liners", J. D. Sethian and A. E. Robson, Journal of Magnetism and Magnetic Materials, 11, 416 (1979).
3. "Equilibrium and Propagation of a Rotating Relativistic Electron Beam", J. D. Sethian, K. A. Gerber, D. N. Spector and A. E. Robson, NRL Memorandum Report No. 4071. (To be published in Phys. Fluids.)

Project

Compact Toroid: Triggered Reconnection Experiment

A. L. Hoffman, E. A. Crawford

FY 79	-	FY 80	\$ 480K op.
	-		\$ 22K eq.

Purpose

Experimental investigation of reverse field theta pinch compact toroid formation using triggered reconnection to induce rapid axial compressional heating. Attempt to produce compact toroids without rotational instabilities and to study their properties. Development of axial heating techniques as opposed to fast radial shock heating.

Approach

A 1-m long, 23 cm core theta pinch is being constructed to operate at 1-2 tesla with high initial reverse bias fields. Quasi-steady mirror/cusp coils are included to delay field line reconnection until the peak magnetic field is reached. Fast mirror coils are used to trigger reconnection at that time. Pulsed octupole rods are included to prevent plasma-wall contact during the field reversal phase, and thus, maximize the trapped reverse bias flux. Provision is made for eventual operation as a compound magnet for extended lifetime studies.

Progress

1. The MSNW LHS laboratory has been completely reconfigured to allow six individual capacitor banks to perform the desired triggered reconnection functions. All electronics and high voltage triggering has been constructed.
2. The individual fast pulsed magnets have been completed and are being cast in urethane for high voltage insulation.
3. Quartz plasma tubes and a cryogenic vacuum system have been ordered.

Plans

1. Study compact toroid formation using various degrees of radial and axial heating.
2. Use diamagnetic loop and magnetic field probe arrays to accurately map compact toroid equilibrium shapes and the effect of the formation process on plasma volume and poloidal flux.
3. Measure plasma density profiles and temperatures.
4. Complete compound magnet and conduct compound magnet experiments.

Milestones

1. Complete electrical system and test magnets.	September 1980
2. Complete plasma and vacuum system.	November 1980
3. Conduct first plasma shot.	December 1980
4. Measure equilibrium shapes using triggered reconnecton.	March 1981
5. Measure toroid density and temperature profiles.	September 1981

Other Professional Staff

D. D. Lowenthal, L. C. Steinhauer, R. D. Milroy, D. C. Quimby

Major Recent Publications

1. A. L. Hoffman, "CT-TRX1: A Triggered Reconnection Compact Toroid Experiment," MSNW Report No. 80-1144-3 (May 1980).

Advanced Fusion Concepts
Naval Research Laboratory

Category: AF/MP

Project
Plasma Containment in Cusp Geometry
R. E. Pechacek
FY 79 \$ OK FY 80 \$ OK

Purpose

To measure the width of the cusp sheath in a plasma-filled magnetic cusp field, in order to determine the plasma loss rate.

Approach

A clean $\beta=1$ plasma is produced from falling D_2 pellets by a ND/GI laser pulse followed by a CO_2 laser pulse. From the center of the cusp field the plasma expands against the field and out the ring and point cusps. Scattered ruby laser light, from a laser pulse that impinges normally on the ring cusp is imaged on a fiber-optic light guide array and analyzed. The result gives the electron density profile in the ring cusp for a single shot.

Progress

The experiment has been completed. Laser scattering diagnostics indicate that the FWHM ring cusp width is about one centimeter. This result agrees with other diagnostics: diamagnetic signals which give the lifetime of the $\beta=1$ plasma, the risetime of the diamagnetic signals and visible light emission and chemical discoloration at the vacuum chamber wall where it intersects the ring cusp. The area of the point cusps is equal to that of the ring cusp, as measured by visible light emission. One centimeter corresponds to the ion gyroradius at the ring cusp, as determined from the local magnetic field and the average total energy of the deuterons.

Plans

Submit for publication an article describing the plasma production system.

Milestones

None

Graduate Students

None

Other Professional Staff

J. R. Greig
Michael Raleigh

Major Recent Publications

"Measurement of the Plasma Width in a Ring Cusp", R. E. Pechacek, J. R. Greig, M. Raleigh, D. W. Koopman, and A. W. DeSilva, Phys. Rev. Lett. 45, 256 (1980).

"The 24" CUSP Experiment", R. E. Pechacek, J. R. Greig, M. Raleigh, D. W. Koopman, and A. W. DeSilva, NRL Memorandum Report 4126 (February 15, 1980).

"Characteristics of a CUSP Laser Plasma Generated from mm-sized D₂ Pellets", R. E. Pechacek, Invited Paper, 1979 IEEE International Conference on Plasma Science (Montreal, June 1979).

Project

High Beta Confinement in Surmac

A. Y. Wong, R. W. Schumacher

FY 79	\$ 350K op.	FY 80	\$ 445K op.
	\$ 50K eq.		\$ 20K eq.

Purpose

Production and diagnosis of high energy density, high beta toroidal multipole plasma and the study of three key physics problems related to the development of Surmac/multipoles into confinement systems for alternate fuel fusion reactors. Key physics problems are:

1. Heat and particle transport scaling at high energy density ($n = 1 - 5 \times 10^{13} \text{ cm}^{-3}$, $T_i \approx 1000 \text{ eV}$).
2. MHD Equilibrium and Stability at finite beta $\leq 15\%$.
3. Magnetic guarding of hoop supports.

Approach

These investigations are being made on the Dodecapole Surmac which is a six hoop toroidal multipole with major radius 45 cm, mean minor radius 15 cm, hoop sum current 500 kA, and peak fields of 5 kG. The plasma source is cross-field coaxial Marshall and Deflagration gun injection through a differential pumping chamber. An upgrade of the magnetic field system, just completed, will increase the hoop sum current to 1.4 MA and the peak field to 14 kG. Neutral beam heating experiments with up to 500 kW of beam power (1.4 W/cm^3 power density) and low energy ($\sim 3 \text{ keV}$), high perveance ion sources are underway.

Progress

1. Obtained collisionless high energy density $\sim 1.8 \text{ MJ/cm}^3$, high beta $\sim 8\%$ Dodecapole equilibrium with plasma parameters $n = 5 \times 10^{13} \text{ cm}^{-3}$, $T_i = 200 \text{ eV}$, $T_e = 25 \text{ eV}$, $v_{ci}/v_{ii} = 18$, $\lambda_{ie}/L = 2$ (where $L =$ connection length), $\tau_E = 90 \text{ } \mu\text{s}$ and $\tau_p = 2 \text{ ms}$. At lower density τ_E increases to $\sim 0.5 \text{ ms}$. A stable equilibrium is observed in excess of 200 Alfvén times with decay time limited by ion charge exchange. The equilibrium is characterized by perturbed internal magnetic fields, flat internal pressure profile with sharp boundary, and a steep hoop bridge pressure profile two ion gyroradii wide centered on the separatrix. The transition from diffuse profiles at low $\beta > 1\%$ to sharp edge profiles at high beta is observed by varying the injected plasma density. A coherent 100 KHz drift-like instability is observed in the poor curvature bridge regions of the average magnetic well when the pressure profile steepens to a scale length $\sim \rho_{ci}$.

2. Completed diagnostic systems include 2 and 4 mm microwave interferometers, charge exchange neutral particle analyzer, 10 channel optical polychromator, UV spectrometer, XUV impurity radiation monitor, and magnetic and electrostatic probes. Diagnostics interfaced to computer Data Acquisition System.
3. Peak ion temperature in equilibrium found to scale as B^2 up to 250 eV.
4. Plasma of density $2 \times 10^{13} \text{ cm}^{-3}$ and mean ion energy $\sim 630 \text{ eV}$ was trapped in the Dodecapole with Deflagration gun injection but no equilibrium obtained. Staged gun injection (Marshall + Deflagration) led to trapping of high density plasma $\sim 5 \times 10^{13} \text{ cm}^{-3}$ at mean ion energy $\sim 500 \text{ eV}$ but again without equilibrium.
5. Injected test neutral beam (2.7 keV, 3 amps) into the Dodecapole and observed trapping and slowing down due to electron drag.
6. Ten channel probe system installed near guarded hoop supports determined width of loss channels encircling supports to be two ion gyroradii.
7. Magnetic field system upgrade consisting of new internal hoops, return current liners, and expanded bank completed.
8. First 150 KW neutral beamline delivered.

Plans

1. Study equilibrium in Dodecapole upgrade with transient gun injected plasma with parameters $n \leq 5 \times 10^{13} \text{ cm}^{-3}$, $T_i \geq 1 \text{ keV}$, $T_e \sim 50 \text{ eV}$.
2. Addition of high temperature plasma diagnostics including:
 - a. Thomson scattering
 - b. Vacuum UV spectrometer
 - c. Multi-channel Charge Exchange Analyzer
 - d. XUV Impurity radiation profile detector array.
3. Investigate MHD stability of poor curvature bridge regions for local beta values $\leq 15\%$.
4. Determine plasma losses due to guarded support perturbations.
5. Study neutral burn-out, electron and ion heating, and heat and particle transport in plasmas sustained with up to 500 KW of neutral beam power.

Milestones

1. Install first 150 KW neutral beam line. August 1980
2. Obtain equilibrium in Dodecapole upgrade with transient parameters $n = 3 \times 10^{13} \text{ cm}^{-3}$, $T_i \leq 1 \text{ keV}$, and $T_e = 30 \text{ eV}$ by gun injection. September 1980

3. Begin construction of two additional neutral beam lines. October 1980
4. Produce first beam sustained 10 ms discharge at $n = 1.5 \times 10^{13} \text{ cm}^{-3}$, $T_e = 80 \text{ eV}$, $T_i = 100 \text{ eV}$. November 1980
5. Documentation of beam driven discharge power balance at 150 KW. August 1981
6. Obtain equilibrium with transient parameters $n = 5 \times 10^{13} \text{ cm}^{-3}$, $T_i = 2 \text{ keV}$, $T_e = 50 \text{ eV}$, $\beta = 10\%$. August 1981
7. Delivery and installation of two additional neutral beam lines September 1981

Graduate Students (% DOE Support)

K. L. Lam (50%), K. Jones (50%), H. Quevedo (50%), G. Hockney (50%),
H. Stephanian (0%)

Graduates (Year)

D. Mamas (1977)
R. W. Schumacher (1979)

Other Professional Staff

M. Fukao, R. G. Suchannek, G. Dimonte, K. Yatsu

Major Recent Publications

1. "Surface Magnetic Confinement," A. Y. Wong, Y. Nakamura, B. Quon, J. Dawson, Phys. Rev. Lett. 35, 1156 (1975).
2. "Surface Magnetic Confinement - A Review," A. Y. Wong, Proceedings of the High Beta Workshop, ed. by E. Oktay, ERDA - 76/108, August 1975.
3. "Surmac: An Advanced Fuel Fusion Reactor," A. Y. Wong, R. W. Schumacher, R. A. Breun, L. R. Miller, Trans. Am. Nuc. Soc. 27, 44 (1977).
4. "Stabilization of Toroidal Currents in High Beta Plasmas by Surface Magnetic Fields," D. L. Mamas, R. W. Schumacher, A. Y. Wong, R. A. Breun, Phys. Rev. Lett. 41, 29 (1978).
5. "High Beta Plasmas in Toroidal Surmacs," R. W. Schumacher, Invited Paper presented at the 20th Annual APS Division of Plasma Physics Meeting, Bull. Am. Phys. Soc. 23, 887 (1978).

6. "Confinement of High Beta Plasmas by Toroidal SURMACS", A. Y. Wong, R. W. Schumacher, D. L. Mamas, Comments on Plasma Physics and Controlled Fusion 4, 3, 65 (1978).
7. "Stable Confinement of High Energy Density High Beta Toroidal Multipole Plasma," R. W. Schumacher, M. Fukao, A. Y. Wong, K. Yatsu, Submitted to Physical Review Letters (1980).
8. "High Beta Confinement Experiments in Multipole/Surmac - A Concept for an Advanced Fuel Fusion Reactor," A. Y. Wong, et al., IAEA Conference, Brussels, Belgium, Paper No. IAEA-CN-38/AA-2, July 1-10, 1980.
9. "Neutral Beam Injection Into Dodecapole Surmac," K. Yatsu, R. W. Schumacher, R. Suchannek, A. Y. Wong, Proceedings of the International Symposium on Physics in Open Ended Fusion Systems, University of Tsukuba, Tsukuba, Japan, April 15-18, 1980.

Project

Levitated Octupole

J. R. Conrad, R. N. Dexter, D. W. Kerst, R. S. Post, S. C. Prager,
J. C. Sprott

FY 80 \$ 295K op.

 \$ 100K eq.

Purpose

To develop heating methods and to study confinement properties of toroidal multipoles.

Approach

A PLT sized levitated toroidal octupole is used to confine plasmas produced by gun injection, ECRH, or ohmic heating and heated by neutral beams and ICRH.

Progress

1. $\beta = 35\%$ plasmas produced at low field with large ion gyroradii.
2. Drift wave instability which is invariant over 3 orders of magnitude in β observed and studied.
3. Anomalous resistivity measured and explained as caused by ion acoustic or ion Bernstein fluctuations.
4. EXB divertor tested and shown to be effective in reducing flux to the wall.
5. Heat transport code written and compared with T_e profile and energy confinement time.
6. Lower hybrid heating tested and found to be highly effective.
7. Machine modifications carried out to allow confinement and diagnostics of hot dense plasmas.
8. Neutral beam sources (2 x 900 kW at 15 keV) nearing completion.
9. ICRH system (2 MW at 2-3 MHz) nearing completion.

Plans

1. Continue gun optimization to measure β limit at low field.
2. Study kinetic corrections to MHD predictions of ballooning instability β limit.

3. Install 1.8 MW neutral beams and 2 MW ICRH.
4. Measure energy confinement of hot, dense plasmas.
5. Increase ring current and pulse length through as second major machine upgrade.

Milestones

1. Install and operate gun capable of separately producing $\beta = 25\%$.	October 1980
2. Complete drift wave eigenvalue calculation for comparison with observed electrostatic instability.	May 1981
3. Demonstrate substantial heating by beams and ICRH.	July 1981
4. Formulate detailed plan for next machine upgrade or new device.	May 1982
5. Characterize quantitatively impurities under RF and neutral beam heated conditions.	June 1982
6. Increase magnetic field limit by 40%.	August 1982

Graduate Students (% DOE Support)

C. Fortgang (100%), H. Garner (100%), J. Halle (100%), A. Kellkman (100%), R. Moyer (100%), S. Painchaud (100%), L. Peranich (0), M. Phillips (100%), E. Rose (100%), J. Twichell (100%), M. Zarnstorff (100%).

Graduates

A. Cavallo (75%), R. Breun (75%), J. Greenwood (75%), G. Navratil (76%), C. Armentrout (77%), A. Butcher-Ehrhardt (78%), E. Strait (79%), D. Brouchous (79%), T. Owens (79%).

Other Professional Staff

R. Torti, E. Strait

Major Recent Publications

1. "Experimental Demonstration of ExB Plasma Divertor," E. J. Strait, D. W. Kerst, and J. C. Sprott, Phys. Fluids 21, 2342 (1978).
2. "Observation of the Effect of Shear on Vortex Diffusion in a Collisional Plasma," G. A. Navratil, R. S. Post, and A. Butcher-Ehrhardt, Phys. Fluids 22, 241 (1979).
3. "Stable Confinement of High Beta Toroidal Plasma," S. C. Prager, J. H. Halle, R. S. Post, and J. Twichell, to Nuclear Fusion, to be published.

Project

Toroidal Plasma Device Featuring Permanent Magnet Cusp Confinement

N. C. Luhmann, Jr.

FY 79	\$ OK op.	FY 80	\$ 20K op.
	\$ OK eq.		\$ OK eq.

Purpose

To produce a high beta plasma without a toroidal field by wall stabilizing a toroidal Z-pinch with permanent magnet cusps.

Approach

Experiments will be performed in a moderate size torus ($R = 45$ cm, $r = 15$ cm). A toroidal current will be induced in the plasma via an iron core, ohmic heating transformer. The plasma will be confined by a combination of the magnetic field generated by the OH current and by rows of permanent magnets arranged in a cusp configuration on the torus exterior. These magnets are placed such that the field on axis is very low (< 30 G).

Progress

1. The stainless steel torus is 80% completed.
2. The vacuum pumping system has been completed and tested to 7×10^{-8} Torr. without bakeout or gettering.
3. A 5 kV capacitor bank with ignitron switching for the OH circuit has been completed and tested.
4. The iron core transformer is 50% completed.

Plans

1. Investigate various breakdown modes including HV pulsing, 30 kHz OH pulses, and ECRH in the cusps at 900 MHz.
2. Induce large toroidal current (> 50 kA) in the breakdown plasma.
3. Observe confinement and heating in the resultant plasma.

Milestones

1. Initial operation - vacuum pumpdown and breakdown plasma.	August 1980
2. Achieve large toroidal current.	October 1980
3. High Density ($n = 10^{13}$ cm $^{-3}$) warm ($T_e = 100$ eV, $T_i = 30$ eV) plasma operation.	December 1980

Graduate Students

M. Rhodes

Major Recent Publications
(New Project)

Laser-Initiated Vacuum Arcs and Advanced Thermonuclear Fuel Studies

J. L. Hirshfield

FY 79	\$ 65K op.	FY 80	\$ 115K op.
	\$ 20K eq.		\$ 0K eq.

Purpose

To investigate magneto-electrostatic ion confinement in a laser-initiated vacuum arc (LIVA); to examine the scaling of such a confinement mechanism over a range of laser powers and discharge currents, and to explore the potential of such an arc for controlled thermonuclear fusion applications.

Approach

1. Experimental: A short intense laser pulse creates a carbon plasma expanding into vacuum. This plasma, containing up to 10^{17} ion-electron pairs, triggers a capacitor discharge in the kiloampere millisecond range. After a selected delay from between one microsecond to several hundred microseconds, a second intense laser pulse blows off more ion pairs from the carbon target. The spatial and temporal evolution of this second laser plasma subject to the self consistent magneto-electrostatic fields of the laser initiated vacuum arc is monitored as follows: Measurements are made of ion flux and energy distributions simultaneously in several directions using electrostatic energy analyzers; of plasma density using the refraction of collimated far infrared laser radiation; of the plasma emission spectrum in the visible and near uv using a 2-meter Ebert spectrometer/polychromator; of escaping ion charge state and energy distributions using an energy/momentum spectrometer. Biomation 805 digital transient recorders enable up to eight data signals from various diagnostics to be recorded simultaneously for each laser shot, thereby enhancing experimental reproducibility. In addition, two PAR 4202 transient signal averagers enable data averaging over several shots to further improve the signal quality.
2. Analytical: A theoretical model is developed for the establishment of an electrostatic wall sheath to prevent escape of the laser produced ions. Calculations are made of the balance between ionization and recombination so as to determine charge state distributions in carbon discharges. Analytical and numerical methods are applied to study thermonuclear and 2-component wet wood burner reactor configurations involving advanced fusion fuel mixes such as $p\text{-}^6\text{Li}$, $p\text{-}^{11}\text{B}$, $p\text{-}^9\text{Be}$.

Progress

1. Upgraded the experimental facility by installation of a 24" diameter stainless steel vacuum vessel and pumping station to serve as the new plasma chamber for LIVA with greatly improved access for diagnostics, and increased time to study sheath formation.

2. Installed a 15J/50MW CO₂ TEA laser for arc initiation. Assembled a Q-switched 1J/10 MW Ruby laser for use as the second laser in the double laser experiment.
3. Measured electron density histories for $n_e < 6 \times 10^{15} \text{ cm}^{-3}$ using far infrared wavelengths.
4. Observed time resolved spectra from lines of various carbon ion stages in attempt to characterize electron kinetics. Optical depth measurements revealed that the LIVA plasma is optically thick to several carbon lines. Observed population inversions in certain lines of Ca impurity ions and H impurity atoms.
5. Using a novel energy/momentum spectrometer developed at Yale, measured the ion composition and energy distributions of individual ion charge states in the laser blow-off plasma as well as the subsequent LIVA discharge plasma.

Plans

1. Conduct extensive measurements of plasma density, ion composition and energy distribution, and plasma line emission in the double laser configuration described above.
2. Extend our electron density measurement capability into the $n_e \lesssim 3 \times 10^{18} \text{ cm}^{-3}$ regime by use of 10.6 μ probe radiation. Improve the time resolution of density measurements by acquisition of Ge:Ga and Ge:Au fast detectors.

Milestones

1. Observe time-dependent spectra from lines of various carbon and impurity atom ion stages in attempt to characterize the electron kinetics and evolution of the delayed second laser blow-off plasma in LIVA. August 1980
2. Determine electron density histories for $n_e < 6 \times 10^{15} \text{ cm}^{-3}$ in LIVA subject to the delayed second laser pulse. September 1980
3. Determine time resolved electron densities near the carbon target for $n_e < 3 \times 10^{18} \text{ cm}^{-3}$ using 10.6 μ radiation and a fast Ge:Au detector. November 1980
4. Measure the ion composition and energy distributions in LIVA subject to the delayed second laser pulse. January 1981
5. Examine the scaling of confined ion lifetime in LIVA to higher currents and laser powers. July 1981
6. Develop numerical code for examining the balance between ionization and recombination so as to determine charge state distributions in carbon discharges. September 1981

7. Upgrade, using latest available cross sections, the numerical code already established for the study of thermonuclear and 2-component wet wood burner reactor configurations using advanced fusion fuel mixes.

November 1981

Graduate Students

J. Trebes

Graduates

M. Mussetto

Other Professional Staff

M. Krishnan, N. Ebrahim, H. Keren

Major Recent Publications

1. "Fast High-Resolution Ion Energy and Momentum Spectrometer," Rev. Sci. Instrum. 51, No. 7, 911 (1980) (with M. Krishnan).
2. "Electron Density Measurement by Deflection of a Far-Infrared Beam," Appl. Phys. Lett. 36, 128 (1980) (with H. Keren).
3. "Measurement of Electron Density Distributions in Laser-Produced Plasmas by Deflection of a Focussed Laser Beam," submitted to App. Phys. Lett. (with H. Keren).

Advanced Fusion Concepts
Princeton Plasma Physics Laboratory

Category: S/T

Project

PLT Stellarator Study

T. K. Chu

FY 79	\$ 150K op.	FY 80	\$ 45K op.
	\$ 0K eq.		0K eq.

Purpose

The purpose of the Stellarator Studies is to:

1. compute the magnetic field configuration of the modular torus with twisted TF (MIT) coils;
2. establish liaison with Los Alamos Scientific Laboratory Reactor Design Group on its reactor study of the MIT-coil reactor concept; and
3. participate in the Wendelstein-VII A experiment of sustaining a stellarator discharge by injecting energetic neutral beams and by reducing or eliminating the ohmic-heating current.

Approach

A stellarator field can be obtained by deforming the toroidal field coils instead of adding helical windings. Since the conductors carry no net toroidal current, the configuration does not require a vertical field. The resultant configuration lends itself to modular construction of a reactor. The present "twisted" TF coil concept differs from that of the "warped" TF coil of Rehker and Wobig in that it includes higher harmonics of the coil deformation so that the coil more closely approximates the helical symmetry of the basic stellarator configuration. The resultant stellarator field has markedly stronger rotational transform than that of the "warped" TF coil concept.

Magnetic-field configurations of the MIT Coil Concept will be computed and machine parameters will be provided to LASL group for a preliminary stress analysis of the coils. Different magnetic-field configurations will be analyzed to determine their suitability to confine a plasma. Close liaison will be established with the LASL Reactor Design Group in this work.

Cooperation with the Wendelstein VII-A Stellarator Group will be carried out by participating in their experiment of sustaining a discharge without the ohmic-heating current by injecting 1 MW beam power.

Progress

1. A PLT Stellarator Scoping Study was completed in FY79. In the study, stellarator physics issues were examined, and a PLT Stellarator conceptual design, and fabrication cost and schedule were provided.

2. As a result of the PLT Stellarator Scoping Study, the concept of modular torus by twisted TF coil was examined; a supplementary report giving preliminary results of the MIT coils was completed and submitted to the Department of Energy in September 1979.
3. The improved MIT concept is based on the addition of higher harmonics to the coil deformation so as to approach more closely the desired helical symmetry.
4. Liaison with LASL and participation in the Wendelstein VII-A experiment have been carried out.

Plans

1. Compute magnetic-field configurations of the MIT coils.
2. Compute forces and stresses in the MIT coils.
3. The adaptability of MIT coils to more complex designs.

Milestones

1. Complete a preliminary report on MIT coils. September 1979
2. Participating in Wendelstein VII-A experiment. April-May 1980
3. Complete survey calculations on MIT coils. September 1980

Graduate Students

None

Other Professional Staff

H. P. Furth, J. L. Johnson, C. Ludescher, and K. E. Weimer.

Major Recent Publications

1. T. K. Chu, J. M. Greene, and J. L. Johnson, "Status of Stellarator Research in Europe", PPPL-TM-308, January, 1978.
2. T. K. Chu, Ed., "A PLT Stellarator Scoping Study", PPPL-TM-328, September, 1979.
3. T. K. Chu and Y. C. Lee, "Energy Confinement Comparison of Ohmically Heated Stellarator to Tokamaks", Nucl. Fusion, preprint PPPL-1618, December 1979.

4. T. K. Chu, H. P. Furth, J. L. Johnson, C. Ludescher, and K. E. Weimer, "Stellarator Field in a Torus with Modular Twisted Toroidal Field Coils" Paper CN-38/BB-1, 8th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels (1980).
5. T. K. Chu, "The W-VII Team's Zero-Current Experiment in the Wendelstein VII-A Stellarator", PPPL-TM-340, July, 1980.

Project

Torsatron Studies

P. Politzer, L. Lidsky, D. B. Montgomery

FY 79 \$ 215K FY 80 \$ 0K

Purpose

1. To develop physics and engineering design criteria for large torsatron/stellarator facilities, including reactor configurations.
2. On the basis of these criteria, to develop detailed designs for "proof of principle" and ignition scale devices.

Approach

Design of large (up to ignition scale) experiments and estimation of the minimum size torstron reactor requires quantitative knowledge of alpha particle confinement, of high energy particle diffusion, of collisional heat transport in both plateau and collisionless regimes, and of beta limitations (due to both equilibrium and stability constraints). The dependencies of these factors on the topology of the stellarator torsatron magnetic fields are being studied both analytically and numerically using a wide array of codes specifically developed for this configuration.

In view of the fact that the first self-consistent overall torsatron reactor study has been completed, engineering studies are concentrating on more detailed engineering design of helical windings, including problems of modularity, structural support, and minimization of support leads.

In conjunction with the improvement of our understanding of the physics and engineering of these devices, the design of a proof of principle device is being refined, and a design is being developed for an ignition scale system.

Progress

1. Our work to date has shown:
 - a. That high energy particle confinement in systems with helical ripple is substantially improved in regimes where the helical ripple is large compared to the toroidal ripple. Extensive numerical calculations demonstrate long term confinement (closed drift orbits) for most of phase space and show that fusion generated alpha particles deposit in excess of 85% of the total alpha energy in moderate aspect ratio systems with helical ripple as high as 10% at $r=0.5a_p$ (a_p = separatrix radius).

- b. Numerical calculations of the ion thermal conductivity in helical toroidal (torsatron) magnetic configurations show the presence of a plateau regime extending over two orders of magnitude in collision frequency. The value of the ion thermal conductivity is approximately equal to the neo-classical plateau for an equivalent torus without helical modulation. The predicted adverse $1/\nu$ behavior due to ripple trapping is not seen.
- c. The helical conductor winding law required for "force-reduced" systems yields flux surfaces compatible with both near term experiment and ignition scale devices. Very small changes in the winding law can lead to substantial further reduction in forces on the helical coils (a small modulation in the winding angle can reduce the maximum force by at least 35%).
- d. The width of the ergodic region at the separatrix is a function of the number and placement of the vertical field coils. Ergodic region thicknesses of $\lesssim 0.05a_p$ can be achieved in properly designed systems.
- e. Vacuum field well depths in excess of 14% can be achieved in $\ell=3$ systems of moderate aspect ratio ($R/a_{coil}=6$) without significant distortion of the separatrix.
- f. The dual constraints of "force-reduced" pitch and minimum blanket thickness constrain the torsatron reactor to $\ell = 3$ systems unless a plasma minor radius in excess of $\sim 3.7m$ is acceptable.
- g. That modularity is attainable in reactor scale systems by utilization of large area resistive joints between superconducting winding segments. A design study assuming the use of high pressure contacts between silver plated joints with $2 \times 10^{-8} \Omega \text{ cm}$ surface resistance predicted $\sim 1.0\%$ electrical recirculating power for joint refrigeration. Resistance values routinely achieved in experiments are a factor of ten or more lower than the assumed value.
- h. The forces in unoptimized reactor-scale systems can be supported by currently available glass-reinforced-epoxy structural elements arranged so that all elements are in either pure tension pure compression. This system is compatible with thermal insulation requirements and the radiation environment expected in an operating commercial reactor.
- i. That a self-consistent design incorporating all known technology and physics constraints can be achieved. This first conceptual reactor design (T-1) also has significant advantages with respect to construction costs and lithium fire safety.

2. Several unique numerical codes have been developed for torsatron systems design and for rapid particle orbit and field calculations. The non-linear multi-parameter optimization code (SOLVE) is used for analysis and optimization of magnetic coil systems. It solves for positions and currents of selected windings when required constraints are specified. These requirements can include geometrical constraints, specification to the magnetic field at many points, specification of flux linkages, and magnetic moments. We have used this code, for example, to design a system in which the flux linking the plasma and the dipole moment of the whole coil set are separately or simultaneously nulled.

Investigation of flux surfaces and particle orbits in three-dimensional systems presents formidable computational problems. For example, an α -particle may make more than 10^5 toroidal transits between birth and eventual loss. The investigation of the development of ergodic magnetic regions also requires exceedingly accurate integration of field lines. We have developed an extremely fast method for calculation of particle orbits and field geometry based on the use of spline interpolation in a series of two-dimensional grids. Multi-dimensional spline interpolation produces smooth representations of $\vec{B}$ and $\nabla\vec{B}$ within the spline grids, and does not produce the numerical divergence of B that is common with other interpolation schemes. The tracking code calculates a B tensor in which $\nabla \times \vec{B}$ and $\nabla \cdot \vec{B}$ are identically zero. This tensor matches the actual slopes of the spline $\vec{B}$ function to seven significant figures near the magnetic axis, and to four significant figures near the separatrix. Spline interpolation reduces the time required for orbit calculations by a factor of 200 from schemes requiring direct evaluations of magnetic fields.

Plans

1. Physics studies will emphasize the investigation of the dependence of key factors (high-energy particle confinement, heat transport, beta limits) on the magnetic topology, particularly the combination of helical harmonics in the field structure and the aspect ratio.
2. Design of an ignition-scale experiment will initially emphasize structural and conductor design, including sensitivity of force distribution and flux surface quality on detailed winding laws.

Graduate Students (% DOE Support)

J. Aspinall (0), J. Johnson (0)

Graduates

R. Potok (1980), T. Uchikawa (1980)

Other Professional Staff

G. Berge, J. Freidberg, L. Lidsky, D. B. Montgomery, N. Pierce,
P. Politzer, D. Sherwell

Major Recent Publications

Research Reports

"Particle Orbits and Diffusion in Torsatrons", R. Potok, L. Lidsky,
and P. Politzer, PFC/RR80-15, 1980.

Technical Reports

"Torsatrons and the Torex Proof of Principle Experiment", P. Politzer,
L. Lidsky and D. B. Montgomery, PFC/TR79-1, 1979.

"Torex IV, a Torsatron Proof of Principal Experiment", P. Politzer,
L. Lidsky and D. B. Montgomery, PFC/TR79-2, 1979.

Journal Articles

"Ion Thermal Conductivity in Torsatrons", R. Potok, P. Politzer, and
L. Lidsky, PFC/JA80-10, 1980, (to be published, Phys. Rev. Lett.,
Oct., 1980).

Project

Wisconsin Torsatron/Stellarator Program

J. L. Shohet

FY 79	\$ 240K op.	FY 80	\$ 275K op.
	\$ 22.23K eq.		\$ 0K eq.

Purpose

1. To maintain the ongoing experimental program, including the operation of the Proto-Cleo stellarator and torsatron, and the design and construction of the IMS modular stellarator experiment.
2. To conduct theoretical investigations of new stellarator/torsatron configurations.
3. To continue with the design of a major stellarator/torsatron physics experiment.

Approaches

1. The IMS device is designed to match the macroscopic magnetic parameters of the Proto-Cleo Stellarator. Side-by-side operation of the two devices will provide a definitive test of the modularity concept in a small-scale device.
2. Studies of the MHD properties of new configurations will be done in collaboration with the Courant Institute at NYU. Studies of vacuum magnetics, coil technology, orbit confinement, neutral injection, and transport will be conducted at Wisconsin.
3. The ongoing design of WISTOR-U will be continued in cooperation with industry.

Progress

1. Parallel gun injection of plasma in the Proto-Cleo stellarator has produced plasmas with densities of 10^{13} per cubic centimeter with lifetimes of 2-4 milliseconds at 3 kilogauss field strength. A new Fabry-Perot interferometer system was used to measure 60 eV temperatures for the high-density gun-injected plasma.
2. A data-acquisition system has been installed on the Proto-Cleo torsatron. Data processing of magnetic probe data has revealed new information regarding fluctuations in the torsatron. Detailed current channel measurements have also been made.

3. The magnetic configuration for IMS has been fixed. Studies of current feeds and field errors are in progress. Force and structural analysis is in progress, in collaboration with the Chicago Bridge and Iron Company. Fabrication methods for the coils are being considered by vendors.
4. MHD studies of the ultimate torsatron have been made in collaboration with NYU. The Betancourt-Garabedian code has been upgraded to allow study of MHD surface modes as well as internal pressure-driven modes. Betas of 4% have been found for the WISTOR-U configuration. The limit is an equilibrium limit rather than a stability limit.
5. Small vertical fields have been found to improve MHD properties in both continuous and modular configurations.
6. Detailed magnetic calculations for WISTOR-U show exceptional magnetic flexibility and stability of surfaces while attaining a variety of rotational transform profiles. Detailed force and stress analysis by Chicago Bridge and Iron Company was used to design a support structure for the helical coil, employing a self-supporting structure inside the vacuum vessel.
7. Numerical calculations have shown the feasibility of efficient neutral injection in the WISTOR-U device.
8. Two experimentalists from Wisconsin participated in work on WVII-a at the Max Planck Institut fur Plasmaphysik at Garching, Federal Republic of Germany. Further ongoing collaboration is planned.

Plans

1. Complete construction of an ECRH source for the Proto-cleo stellarator, and the IMS device. Further Proto-Cleo experiments will include separatrix heating, current profile measurements, ICRH, and RF-driven current studies.
2. Design, engineering, testing, and construction of the IMS experiment.
3. Conduct MHD calculations for modular configurations. Develop capability for thermal transport calculations in various configurations. Upgrade neutral beam code for modular configurations.
4. Continue engineering design for the WISTOR-U experiment. Develop a cost analysis, construction schedule, and management plan.

Milestones FY 80

1. Data acquisition system operational on Proto-Cleo torsatron. Magnetic fluctuation and current profile measurements begun.	November 1979
2. Equilibrium beta limit of 4% calculated for internal pressure-driven modes in WISTOR-U configuration. Additional vertical field found to improve MHD characteristics.	March 1980
3. Ultimate stellarator configuration discovered. Leads to improved modular stellarator configurations.	April 1980

4. Fabry-Perot interferometer and improved Bostick-type gun operational on Proto-Cleo stellarator. May 1980
5. IMS magnetic configuration fixed. June 1980
6. Current feed and support structure design for IMS complete. August 1980
7. ECRH on Proto-Cleo stellarator with new source. October 1980

Milestones FY 81

1. MHD studies of the WISTOR-U configuration complete. December 1980
2. Joint research with Chicago Bridge and Iron Company for force and strain data analysis of WISTOR-U and reactor configuration support structures. March 1981
3. IMS acceptance testing completed. Machine moved to Torsatron/Stellarator Laboratory to occupy old torsatron bed. Conversion of bus bars, controls. July 1981
4. First plasma in IMS. Gun plasma studies begin. August 1981

Graduate Students

1. David T. Anderson	9. Richard L. Bonomo
2. Jeffrey H. Harris	10. Robert Schill
3. Joseph N. Talmadge	11. Thomas A. Casper
4. Jon D. Treffert	12. Randy C. Schaeffer
5. Thomsas W. Kruckewitt	13. Darius Wroblewski
6. Daniel J. Hoffman	14. James A. Derr
7. Mark Schmidt	15. Luis Goes
8. Paul H. Probert	16. Andre Plasson

Graduates

Thomas A. Casper	Doctor of Philosophy
James A. Derr	Master of Science
Thomas W. Kruckewitt	Master of Science
Randy C. Schaeffer	Master of Science

Other Professional Staff

T. D. Mantei, Visiting Professor
 James A. Derr, Specialist
 David T. Anderson, Specialist
 Tony Piccione, Specialist
 Kathie J. Kinnaman, Secretary
 Francis Bauer, Consultant (from Courant Institute)
 Octavio Betancourt, Consultant (from Courant Institute)
 Paul Garabedian, Consultant (from Courant Institute)
 John Tataronic, Consultant (from Courant Institute)

Major Recent Publications

1. D. T. Anderson, J. A. Derr, T. W. Kruckewitt, J. L. Shohet, J. A. Tataronis, and S. Rehker, Particle Orbits, Magnetic Surfaces, and Neutral Injection in Stellarators, Torsatrons, and Ultimate Torsatrons, Proc. 8th European Conf. on Plasma Physics and Controlled Fusion Research, (Oxford, 1979).
2. J. A. Derr and J. L. Shohet, Superbanana Orbits in Stellarator Geometries, Phys. Rev. Lett. 43, 1730 (1979).
3. W. L. Waldron, J. H. Hopps and J. L. Shohet, Surface Modes in Magnetized Fully Ionized Plasmas, Phys. Fluids 23, 129 (1980).
4. D. T. Anderson, J. L. Shohet, S. Rehker and J. A. Tataronis, Neutral Beam Injection Calculations for Torsatrons, Nucl. Fusion 20, 197 (1980).
5. T. A. Casper and J. L. Shohet, Low Frequency Density Fluctuations in the Proto-Cleo Torsatron, to be published in Nuclear Fusion.
6. R. C. Schaeffer and J. L. Shohet, Current Density Profile Measurements in the Proto-Cleo Torsatron, IEEE Transactions on Plasma Science, PS-8, 120 (1980).
7. E. S. Fairbanks and J. L. Shohet, Electron Beam Measurements of the Magnetic Surfaces in the Proto-Cleo Torsatron, IEEE Transactions on Plasma Science, PS-7, 94 (1979).
8. T. W. Kruckewitt and J. L. Shohet, Magnetic Properties of Ultimate Torsatrons, submitted to Nuclear Fusion.
9. J. A. Derr and J. L. Shohet, Modularity of Ultimate Stellarators, submitted to Nuclear Fusion.
10. D. J. Hoffman, J. N. Talmadge and J. L. Shohet, Plasma Gun Injection in the Proto-Cleo Stellarator, submitted to Phys. Rev. Lett.
11. J. L. Shohet, Stellarators (chapter in Fusion, Edward Teller, Editor), Academic Press, Inc., New York (to be published).
12. F. Bauer, O. Etancourt, P. Garabedian and J. L. Shohet, Beta Limits for Torsatrons, submitted to Phys. Rev. Lett.
13. D. T. Anderson, et al., Recent Progress in Torsatron/Stellarator Research in the USA, IAEA Conf. on Plasma Physics and Controlled Fusion Research (Brussels, 1980).

Project

Scylla IV-P

R. E. Siemon, K. F. McKenna

FY 79	\$1200K op.	FY 80	\$ OK op.
	\$ 200K eq.		\$ OK eq.

Purpose

To investigate and develop concepts that would improve the axial confinement properties of linear high-density magnetic fusion devices.

Approach

Solid end plugs, i.e., material barriers to stop axial plasma flow, were used at the ends of a 5-m linear theta pinch. Thomson scattering, excluded flux, several interferometer configurations, neutron emissions, streak cameras, and other diagnostics were used to document the resulting improved confinement and to determine the losses resulting from electron thermal conduction.

Progress

The major result was that the LiD end plugs stopped the axial flow of deuterium plasma ($T_e \sim 2$ keV, $n \sim 10^{16} \text{ cm}^{-3}$) resulting in a significant (3x) improvement in energy confinement ($\tau_E \sim 5 \times 10^{-11} \text{ sec/cm}$). In contrast, quartz and BN end plugs resulted in only slightly reduced plasma flow when compared with open-ended operation. Thomson scattering measurements of T_e at various times and axial positions indicate that the overall electron energy balance is consistent with classical expressions for thermal conduction parallel to a magnetic field.

Plans

Reactor extrapolations based on classical electron thermal conduction are not generally favorable. This experiment has been terminated and activities have been redirected to the LASL Compact Toroid and Reversed Field Pinch Programs.

Milestones

N/A

Graduate Students

N/A

Graduates

N/A

Other Professional Staff

R. R. Bartsch, R. J. Commisso, C. A. Ekdahl, and G. Miller

Major Recent Publications

1. "Solid End-Plug Experiment on a Theta Pinch," R. J. Commisso, G. A. Ekdahl, K. B. Freese, K. F. McKenna, and W. E. Quinn, Phys. Rev. 39, 137 (1977).
2. "End Loss from a Collision-Dominated Theta-Pinch Plasma," K. F. McKenna and T. M. York, Phys. Fluids 20, 1556 (1977).
3. "Recent Developments in Linear Theta-Pinch and Laser-Heated Solenoid Research," (joint paper) K. F. McKenna, R. R. Bartsch, R. J. Commisso, C. A. Ekdahl, K. B. Freese, R. F. Gribble, F. C. Jahoda, G. Miller, R. E. Siemon, J. U. Brackbill, J. P. Freidberg, S. P. Gary, H. R. Lewis, A. G. Sgro, L. Turner, D. Winske, A. L. Hoffman, E. A. Crawford, D. D. Lowenthal, D. C. Quimby, G. C. Vlases, H. W. Hoida, and Z. A. Pietrzyk in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf. Innsbruck, 1978) Vol. 2, IAEA, Vienna (1979) 229.
4. "Neutron Diagnostics for Pulsed High-Density Thermonuclear Plasmas," C. A. Ekdahl, Rev. Sci. Instrum. 50, 941 (1978).
5. "Energy- and Particle-Confinement Properties of an End-Plugged, Linear Theta Pinch," R. J. Commisso, R. R. Bartsch, C. A. Ekdahl, K. F. McKenna, and R. E. Siemon, Phys. Rev. Lett. 43, 442 (1979).
6. "Collisionless Flow and End Loss from a High-Energy Theta-Pinch Plasma," K. F. McKenna, R. R. Bartsch, R. J. Commisso, C. A. Ekdahl, W. E. Quinn, and R. E. Siemon, Phys. Fluids 23, 1443 (1980).
7. "The Rotational Instability in a Linear Theta Pinch," C. A. Ekdahl, R. R. Bartsch, R. J. Commisso, R. F. Gribble, K. F. McKenna, G. Miller, and R. E. Siemon, (Phys. Fluids, to be published).

Project

Laser Heated Solenoid

A. L. Hoffman, D. D. Lowenthal

FY 79 \$ 450K op. FY 80 (funding terminated)
 \$ 100K eq.

Purpose

Experimental investigation of the fusion concept based on a laser heated, high density magnetized plasma in a long linear solenoid. Basic radial and end loss measurements in support of linear magnetic fusion.

Approach

A 3-m long, 3.8 cm bore, fast pulsed solenoidal magnet is used to confine ~ 1 cm diameter plasma columns which are heated with a multi kJ pulsed CO₂ laser. The size, or line density of the plasma column needed to maintain the density minimum required for beam trapping is investigated. Plasma energy is measured every half meter with diamagnetic loops, laser energy transmitted through the column is measured with a time dependent spatially averaged detector, and density profiles are measured with a multichannel interferometer.

Final Accomplishments

1. Laser beam trapping and plasma column heating at 1 kJ/m levels has been accomplished in a 3-m long, 2.5 cm bore plasma tube using 3 kJ of incident laser energy. Once created, on axis density minimums can be maintained for times governed by classical field diffusion.
2. Density minimums can be created over the full column length when the laser irradiation begins near the solenoidal field initiation. In this mode of operation, the absorption length is initially long and decreases with time due to the ring confinement pressure. This initially long absorption length allows propagation to occur over large distances without firing individual solenoidal modules in sequence. The measured energy deposition time histories agree very well with simple one-dimensional axial modeling assuming that about 2/3 of the incident laser radiation is trapped, and about 1/2 of the plasma column line density is heated to peak temperature.
3. A unique cross tube, 10 channel, time dependent interferometer has been developed which permits accurate radial density profiles to be made through a 2.5 cm bore plasma tube with 1 mm spatial and 50 nsec temporal resolution.

4. Plasma electron densities, diamagnetism, and optical emission have been measured at the magnet center where the plasma properties are unaffected by end loss. Typical plasma conditions at 6 tesla fields are peak temperatures of 100 eV and central densities of $5 \times 10^{17} \text{ cm}^{-3}$. The plasma column loses energy on a timescale consistent with classical cross-field thermal conductivity to a cold boundary layer (5 - 10 μsec). The energy loss rates are modeled accurately with a one-dimensional radial MHD code by assuming minute ($\sim 0.1\%$) quantities of wall impurities present at the column edge. These impurities are seen spectroscopically and are assumed to be produced by the combination of high plasma energy density and small tube diameter.

Conclusions

1. The technique of laser heating magnetically confined plasmas has been developed and demonstrated over a length to plasma column diameter of about 300.
2. Classical radial energy confinement has been demonstrated, limited only by the presence of wall impurities at the column edge.

Other Professional Staff

E. A. Crawford, L. C. Steinhauer, D. C. Quimby, R. D. Milroy

Major Recent Publications

1. D. D. Lowenthal, "Quasiquadrature Interferometer for Plasma Density Radial Profile Measurements: Achieving Ten Channel Operation," Rev. Sci Instr 51, 440 (1980).
2. A. L. Hoffman and D. D. Lowenthal, "Axial Laser Heating of Three Meter Theta Pinch Columns," MSNW Report No. 79-1045-5; also Phys. Fluids 23, (1980).
3. D. D. Lowenthal, D. C. Quimby and A. L. Hoffman, "Radial Plasma Measurements and Calculations in the Center of a Three Meter Laser Heated Theta Pinch," MSNW Report No. 80-1045-8.

Project

Multiple Mirror Plasma Confinement

A. J. Lichtenberg and M. A. Lieberman

FY 79	\$ 175K op.	FY 80	\$ 125K op.
	\$ 19K eq.		\$ 25K eq.

Purpose

To determine the characteristics and applicability of multiple mirror confinement of linear magnetic fusion systems. The entire device may consist of mirrors or may use multiple mirror sections providing end stoppers for a constant central magnetic field region.

Approach

A 10 meter long, eleven cell, 20 kG peak mirror field, quadrupole stabilized, multiple mirror device with hydrogen plasma injected from a O-pinch is used to make accurate measurements of multiple mirror diffusion and to test average minimum B stability flute modes and ballooning modes at significant . A three meter seven cell multiple mirror operated either with a conical O-pinch source, or a contact ionization source is used to explore new ideas concerned with multiple-mirror confinement.

Progress

1. Injection into the 10 meter multiple mirror has been accomplished using both a coaxial Marshall gun source and a conical O-pinch source, injecting both single-ended and double-ended. Injection was accomplished both into static fields and into rising mirror and quadrupole fields, with the latter achieving more uniform injection . At $n \sim 10^{13}$ and $T \sim 10$ eV the confinement was experimentally determined and good agreement found with theory. At $n \sim 10^{14}$ (β of a few percent) the confinement time is determined by radial loss and good agreement was obtained with the prediction from classical loss processes. Stable decay for β 's up to ten percent was achieved for magnetic fields predicted to be stable to flute modes at low β .
2. The small experiment was modified to allow axial feedback stabilization with a plasma injected from a Marshall gun source. Experiments will be begun shortly.
3. Reactor design studies have been refined to include effects such as particle pressure and the stairstep pattern of the density. An economic analysis has been performed to determine the range of Q-values that achieve minimum cost at a fixed power out. A number of possibilities for improving the Q have been considered, including β -optimization, non-adiabatic scattering, and traveling wave mirrors. Large improvements in system performance were found to be theoretically possible.

Plans

1. Determine the effect of significant β on stability for magnetic field shapes near marginal stability.
2. Excite ballooning mode instabilities by destabilizing two cells and determine the characteristics of the modes.
3. Determine the effect of finite β on axial confinement and radial loss.
4. Measure diffusion across the magnetic field in the presence of the distorted average minimum-B flux surfaces.
5. Feedback stabilize an injected plasma.
6. Continue theoretical studies of stability and diffusion in support of the experiments.

Milestones (July 1, 1980 - June 30, 1981)

1. Upgrade O-pinch source to attain $T_c \approx T_i > 50$ eV.
Measure temperature spectrographically. July 1980
2. Demonstrate transition from stable to unstable behavior due to flute and ballooning instabilities with increasing beta by weakening average well. September 1980
3. Produce ballooning instabilities by destabilizing two cells. November 1980
4. Investigate theoretically the interaction between collisional processes and ECRH on heating and diffusion. December 1980
5. Measure losses due to radial transport and compare with classical theory. February 1981
6. Complete flute and ballooning instability studies. June 1981

Graduate Students (% DOE Support)

H. D. Price, 100%, R. Bravenec, 100%; K. Donninger, 50%; F. Najmabadi, 100%

Graduates

J. Riordan, M. Tuszewski, (1978); S. T. Yang (1979); S. L. Wong (1979)

Other Professional Staff

Dr. M. Tuszewski (Assistant Research Engineer)

Major Recent Publications

1. J. C. Riordan, M. Tuszewski and A. J. Lichtenberg, "Stabilization of Interchange Modes in Multiple Mirror Confined Plasma", Plasma Physics 20, 139 (1978).
2. R. R. Dominguez and H. L. Berk, "Stability of Interchange Modes in a Hot Electron Plasma", Phys. Fluids 21, 827 (1978).
3. H. L. Berk and R. R. Dominguez, "Variational Method for Electromagnetic Waves in a Magneto-Plasma", J. Plasma Phys. (1978).
4. J. C. Riordan, A. J. Lichtenberg and M. A. Lieberman, "Minimum-Average-B Wells in Linked Magnetic-Mirror Fields", Nuclear Fusion 19, 21 (1979).
5. M. Tuszewski et al., "MHD-Stabilization of Finite- Multiple-Mirror Plasmas", Nuclear Fusion 19, 1245 (1979).
6. F. Najmabadi, A. J. Lichtenberg and M. A. Lieberman, "Coil Design and Economic Optimization for Multiple-Mirror Fusion Reactors", Proceedings of 8th Symposium on Engineering Problems in Fusion Research, IEEE, San Francisco, California, November 13-16, 1979.

Project

Comparative Study of LINUS Plasma Preparation

G. C. Vlases, A. L. Hoffman, T. L. Churchill

FY 79 \$ 200K op. FY 80 \$ OK op.

 \$ OK eq. \$ OK eq.

Purpose

Analyze approaches for preparing the plasma of a LINUS type device and choose the approach which has the best chance of producing plasmas for a LINUS compression experiment in two year timescale. Recommend a program plan for development of this technique.

Approach

1. Consult with a "panel of experts" to establish consensus for the best plasma configuration and generation technique.
2. Conduct detailed analysis of this plasma configuration and generation.
3. Utilize available sources such as SAI for anomalous transport and Courant Institute for equilibrium calculations to help define the concept performance.
4. Develop engineering development plan for chosen technique.

Progress

This project has been satisfactorily completed and the final report has been received by the Department of Energy.

Milestones

1. Panel of experts meeting.	November 1978, Completed
2. Preliminary choice of filling technique.	November 1978, Completed
3. Subcontracts to SAI and Courant.	December 1978, Completed
4. Presentation to NRL on Findings.	February 1979, Completed
5. Final presentation to DOE.	April 25, 1979, Completed
6. Final Report to DOE.	May 1979, Completed

Other Professional Staff

L. Steinhauer, D. Quimby, R. Milroy, E. Crawford, D. Lowenthal, T. DeHart.

Consultants

Fred Ribe, Adam Pietrzyk

Subcontractors

Sishi Hamasaki, Bill Grossmann

Panel of Experts

R. Linford, T. Jarboe, A. Robson, J. Sethian, N. Rostoker, H. Fleischmann
C. Hartman.

Project

Fast Liner Experiment

A. R. Sherwood

FY 79	\$ 250K op.	FY 80	\$ OK op.
	\$ 10K eq.		\$ OK eq.

Purpose

To investigate the imploding liner approach to fusion in the liner velocity regime where wall-confined plasmas are a possibility.

Approach

The implosion of thin, cylindrical, nonrotating metallic liners is being studied using a portion of the Scyllac bank. The liners are magnetically imploded by the pinch force from a multimegamp current flowing in the liner parallel to its axis. The symmetry and velocity of the implosions are compared with theoretical models. Simultaneously experiments are underway leading towards the production of a suitable plasma load for the imploding liner. A warm (100-300 eV), dense ($10^{17} - 10^{18} \text{ cm}^{-3}$), plasma with an embedded magnetic field is required. So far, these plasma preparation experiments have been based on coaxial gun and hardcore pinch concepts.

Progress

1. A series of liner implosion tests was carried out, with a steady improvement in the diagnostics. The liner trajectories are in excellent agreement with theory. Velocities of $4-6 \times 10^5 \text{ cm/sec}$ are being obtained, exceeding by a factor of 3-4 the velocities achieved by the Soviets for similar-sized liners.
2. The three final shots, at increased bank energy (2.4 MJ), achieved velocities of $.9-1.0 \times 10^6 \text{ cm/sec}$, the highest ever achieved by capacitor bank driven liners. Flash X-ray pictures indicated gross symmetry during the implosion, but additional measurements are needed to fully characterize the degree of symmetry.
3. Several different geometries have been tried for conducting the plasma from a 30-cm-o.d. plasma gun into an implodable geometry. Plasmas having the parameters $3 \times 10^{16} \text{ cm}^{-3}$, 40 eV, and 10 kG have been obtained, but the impurity level is unknown. These parameters are all about a factor of 3 short of what is required for an interesting liner plasma.
4. A hardcore pinch geometry for producing a liner plasma was also tried. The plasma generation by the pinch worked as designed, and the plasma flowed into a liner region at one end of the pinch as expected. The magnetic field in the plasma in the liner region was about 10 kG. Measurements of other plasma parameters were inconclusive when the work was halted.

Plans

For programmatic reasons, a decision was made within DOE to shift this program from the Office of Fusion Energy, ET, to DP, DOE. Programmatic control was so shifted as of January 1, 1979, but the funding status of the program within DP is still unclear. The following plans and milestones assume continuation of the funding under DP.

1. Continue to refine the diagnostics in order to more fully establish the symmetry of the liner implosions.
2. Finish the refurbishing, installation, and shakedown of an additional four racks of the Scyllac bank. This will allow operation at a lower bank voltage at the present energy of 1.75 MJ, as well as an increase in the bank energy to about 3 MJ.
3. Establish the parameters of the plasma being produced by the new hardcore pinch geometry.

Milestones

1. Complete the addition of four more racks of the Scyllac bank to the liner implosion experiment - 4 months after funding (MAF).
2. First liner implosions at increased bank energy - 5 MAF.
3. Plasma preparation experiments carried to the point that preparations for liner implosions on a plasma can begin - 9 MAF.
4. First liner implosion upon a suitable plasma - 22 MAF.

Graduate Students

None

Graduates

None

Other Professional Staff

J. Marshall, T. R. Jarboe, I. Henins, E. L. Cantrell, H. W. Hoida

Major Recent Publications

1. E. L. Cantrell, R. A. Gerwin, I. Henins, T. R. Jarboe, R. C. Malone, J. Marshall, R. W. Moses, G. A. Sawyer, A. R. Sherwood, B. R. Suydam, C. E. Swannack, "Experimental and Theoretical Liner Fusion Studies", Proceedings of Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria (1978).

2. A. R. Sherwood, E. L. Cantrell, C. A. Ekdahl, I. Henins, H. W. Hoida, T. R. Jarboe, P. L. Klingner, R. C. Maline, J. Marshall, G. A. Sawyer, "Results from the Los Alamos Fast Liner Experiment,: Proceedings of the Second International Conference on Megagauss Magnetic Field Generation and Related Topics, Washington, D. C. (1979).
3. R. A. Gerwin, R. C. Malone, "Adiabatic Plasma Heating and Fusion-Energy Production by a Compressible Fast Liner," Nuc. Fusion 19, 155 (1979).
4. F. L. Ribe and A. R. Sherwood, "Fast Liner-Compression Systems," (contribution to the book FUSION, E. Teller, Editor).
5. A. R. Sherwood, E. L. Cantrell, I. Henins, H. W. Hoida, T. R. Jarboe, R. C. Maline, J. Marshall, "The LASL Fast Liner Experiment," (to be published in Eighth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium, [1980]).

Advanced Fusion Concepts
Lawrence Berkeley Laboratory

Category: Tormac

Project

Tormac

M. A. Levine

FY 79	\$ 600K op.	FY 80	\$ 35K op.
	\$ 50K eq.		\$ 0 eq.

Purpose

Investigate the heating and confinement of plasma in Tormac and develop a method of plasma injection in a quasi-steady state device. Tormac consists of a central toroidal plasma on closed magnetic flux tubes surrounded by a sheath of open magnetic field lines where plasma is mirror contained. The plasma is confined to a region in which the magnetic field intensity has a minimum even when the plasma is not present.

Approaches

1. Use the Tormac PI (Puffer) plasma gun to pulse fill a toroidal bicuspid. This will present a plasma of suitable temperature and density for the equilibrium and transport measurements.
2. Use Tormac IV and V to develop a pulse option for Tormac start-up and equilibrium studies. These are .5m and 1m diameter glass vessels equipped with pulsed capacitor systems for preionizing, preheating and forming a bicuspid.

Progress

1. Measurements were completed on Tormac V which indicated that the desired Tormac equilibrium could not be reached with the relatively slow application of magnetic field available in Tormac V.
2. Measurements were completed on Tormac IV which indicated low temperatures and lack of a Tormac equilibrium. Comparison of Thomson scattering measurements, probe measurements and spectroscopic measurements revealed a discrepancy. While the spectroscopic measurements showed high temperatures under same circumstances, the more direct and reliable scattering and probe measurements, gave temperature near 10 eV. The discrepancy has subsequently been explained.
3. The Puffer gun assembly was tested and was able to deliver as much as 1000 Joules of energy to a toroidally expanding plasma. Thus 5×10^{18} protons with directed energies of 1000 eV/particle were shot out in a configuration that can be described as a radially expanding Tokamak, Mach 5, $q = 1$. The output power was over 30% of the energy stored in the driving capacitor, and was higher than anticipated. Thus, the system was never run at more than 50% of its rated energy.

4. Tests of stopping the plasma were performed with a 140 eV directed energy plasma. Results indicated that a shock was created as predicted and that the plasma could be stopped, and a Tormac equilibrium filled. Scattering measurements gave electron temperatures in the 10 - 20 eV range as predicted. A particle collector along the open field lines showed the sharp sheath characteristic of the predicted Tormac equilibrium. Tests with the high-energy particle pulses were inconclusive since the project was terminated for lack of funds before measurements could be made.

Plans

Discontinued.

Graduates

J. Coonrod, M. Greenwald, R. S. Shaw.

Other Professional Staff

I. G. Brown; W. Harris, B. R. Myers, B. Feinberg; R. A. Niland; P. A. Pincosy; and L. Soroka.

Major Recent Publications

M. A. Levine, "The Use of a Hot Sheath Tormac V Experiment," LBL-6385, July 1977.

I. G. Brown, W. B. Kunkel, and M. A. Levine
"Tormac Reactor Considerations" Nucl. Fusion 18, 761 (1978).

B. R. Myers and M. A. Levine
"Two-dimensional Spectral Line Emission Reconstruction as a Plasma Diagnostic" R.S.I. 49, 610 (1978).

Levine, Berk, Brown, Coonrod, Feinberg, Greenwald, Hammer, Kunkel, Myers, Niland, Sessler, Sharp, Shaw, Soroka, Vella, Boozer, Mostrom, and Gladd, "Tormac Confinement, Theory and Experiment," Proc. 7th Inter. Conf. on Plasma Physics and Controlled Fusion, Vol. II, p. 81. (Innsbruck, Austria, August 1978), IAEA-CN-37-E-4, Vienna (1979) LBL-7960.

Levine, Kunkel, Brown, Feinberg, Myers, Niland, Coonrod, Greenwald and Shaw
"Tormac Experiment," EPRI Report, Contract No. RP 272.

J. W. Coonrod, Jr.
"Density and Magnetic Field Measurements in Tormac IV-C Plasma," Ph.D. Thesis, LBL-8167, September 1978.

M. J. Greenwald, "Temperature Measurements in the Tormac IV-C Plasma," Ph.D. Thesis, LBL-8166, September 1978.

Myers, Levine and Pincosy, "Toroidal Plasma Gun," LBL-9507,
August 1979.

Myers, Levine and Shaw, "A Fast Opening Gas Valve," LBL-10459,
February 1980.

Shaw, Coonrod, Greenwald, Levine, Myers and Vella, "Observation
of Anomalously Broad Gaussian He II 4686 A Spectral Lines in Tormac,"
LBL-10218, March 1980.

Brown, Feinberg, Kunkel, Levine, Niland, Shaw and Vaucher, "The Tormac
V Experiment," LBL-10586, March 1980.

R. S. Shaw, "A Study of Ion Line Broadening in the Tormac Discharge,"
Ph.D. Thesis, LBL-10748, 1980.

Feinberg, Shaw, Vancher, and Vella, "Magnetic Field Penetration in
Tormac V," LBL-10318, 1980.