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Mirror Confinement Systems

Project Summaries

April 1980

Published July 1980

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U.S. Department of Energy
Office of Energy Research
Office of Fusion Energy
Division of Mirror Confinement Systems

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Division of Mirror Confinement Systems
W. R. Ellis, Acting Director

U.S. Department of Energy
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Division of Mirror Confinement Systems
Washington, D.C. 20545

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PREFACE

This report contains descriptions of the projects supported by the Mirror Confinement Systems (MCS) Division of the Office of Fusion Energy. The individual project summaries were prepared by the principal investigators, in collaboration with MCS staff office, and include objectives and milestones for each project. In addition to project summaries, statements of Division objectives and budget summaries are also provided.

This document will be distributed to various segments of the fusion community. For scientists in the field it is intended to provide the information about on-going projects needed to improve communications among laboratories and with the Division. For the Office of Fusion Energy, it will contribute to the understanding, coordination, and management of projects by the Office of Fusion Energy staff.

William R. Ellis, Acting Director
Division of Mirror Confinement Systems
Office of Fusion Energy

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Acknowledgement

This document would not exist in its present form without the efforts of Ms. Lee Neighbors of New York University, who spent several months in 1979-1980 working in the Department of Energy, Germantown, with the Mirror Confinement Systems Division. Her efforts are gratefully acknowledged.

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INTRODUCTION

The Mirror Confinement Systems Division manages several main-line mirror facilities designed for research on specific technical problem areas such as plasma heating parameter scaling, and increasing the energy amplification of the reactor (Q-enhancement).

The primary experiments designed to investigate and resolve these technical problems are the Tandem Mirror Experiment (TMX), Phaedrus, Symmetric Tandem Mirror (STM), Beta II, and Elmo Bumpy Torus (EBT). Each experiment provides a specific emphasis. TMX and Phaedrus are both tandem mirror experiments. TMX emphasizes neutral beam heating while Phaedrus, a smaller experiment, focuses on rf heating. Beta II investigates the reversal of magnetic fields deep in the plasma. Experiments with the EBT device emphasize steady state, toroidal mirror operation. The STM experiment studies tandem mirror end plugs for improved symmetry, making use of rf techniques similar to those used in EBT.

Supporting experiments recently managed by the Mirror Confinement Systems Division include the Field Reversal Experiment (FRX) at Los Alamos Scientific Laboratory, Plasma Stabilization Experiment (PSX) at United Technology Research Corporation, and the Constance II device at Massachusetts Institute of Technology. The properties of plasma confined in a field reversed configuration are investigated in FRX. In PSX and Constance II, stabilization of drift cyclotron loss cone (DCLC) modes of a mirror confined plasma using rf techniques are studied. These supporting projects, which tend to be smaller in size and budget than the main confinement experiments, are managed in close cooperation with OFE's Division of Applied Plasma Physics (DAPP). Management responsibilities for some of these projects were recently transferred formally to DAPP.

The Mirror Fusion Test Facility (MFTF) is the major scaling experiment in the mirror program. MFTF may be operated in different modes to investigate issues relevant to tandem mirror devices, field-reversed mirror devices, or both. In the spring of 1980, following a series of highly supportive technical reviews, DOE approved the conversion of MFTF into a tandem mirror machine with thermal barriers, MFTF-B, to operate in the 1984-1985 time frame. MFTF is located at the Lawrence Livermore Laboratory.

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Mirror Confinement Systems Division

PERSONNEL

<u>Staff Member</u>	<u>Area of Responsibility</u>
William R. Ellis	Director (Acting)
T. V. George	Phaedrus, Constance II, FRX, Beta II
Robert E. Price	TMX, MFTF
James M. Turner	EBT, STM
Lee A. Neighbors	(Visiting from NYU)
Cynthia A. Smith	Secretary

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FUNDING SUMMARY
(In Thousands of Dollars)

	<u>FY 1979</u>	<u>FY 1980</u>
Operating Budget		
LLL	\$14,030	\$15,500
LASL	320	500
U. of Wisconsin	650	869
MIT	0	242
TRW	212	730
UTRC	140	160
SAI	102	40
U. of Iowa	0	25
NYU	0	20
Johns Hopkins	56	0
UC-Berkeley	0	46
RPI	0	18
ORNL	<u>4,240</u>	<u>8,875</u>
Total Operating	\$19,750	\$27,025
Equipment Budget		
LLL	\$ 3,169	\$ 3,200
LASL	50	100
U. of Wisconsin	100	150
MIT	0	50
TRW	0	50
U. of Iowa	0	25
ORNL	<u>300</u>	<u>775</u>
Total Equipment	\$ 3,619	\$ 4,350

Mirror Confinement Systems

Lawrence Livermore Laboratory (LLL)

Project

Tandem Mirror Experiment (TMX)
F. H. Coensgen and T. C. Simonen

OFE Contact

Robert E. Price

Purpose and Relationship to Other Projects

TMX is the first device in the U.S. to test the principles of the tandem mirror concept for Q-enhancement. The experiment was basically designed with information acquired from the 2XIIB mirror experiment. The TMX end plugs are similar in size to those in 2XIIB. TMX has served as a proof-of-principle experiment for the tandem mirror concept and provided the basis for consideration of the conversion of MFTF to the tandem mirror configuration as MFTF-B. With upgrade, the TMX experiment (TMX-U) will provide scaling data and examine relevant physics issues.

Approach

The TMX approach is to test the tandem concept, namely using two 2XIIB sized mirrors as electrostatic plugs for axial confinement of a solenoidal plasma. The plug is maintained at high density by neutral beams, thereby creating a positive potential barrier with respect to the plasma in the solenoid. Plasma confinement in the solenoid is thus enhanced because the ions must be up-scattered in energy over the potential barrier to escape. The plasma leakage from the solenoid plasma also serves to stabilize the mirror confined plug plasma against loss cone modes.

Parameters

A. Machine:

	<u>Center Field</u> <u>(kG)</u>	<u>Axial</u> <u>Length</u> <u>(m)</u>	<u>Plasma</u> <u>Radius</u> <u>(m)</u>	<u>Pulse</u> <u>Length</u> <u>(sec)</u>	<u>Mirror</u> <u>Ratio</u>
End Plugs	20	0.9	0.2	0.025	2
Solenoid	0.5-2	5.5	0.7		20-80

B. Plasma (maximum achieved):

	<u>n_i (cm⁻³)</u>	<u>T_i (keV)</u>	<u>T_e (keV)</u>	<u>τ_c (ms)</u>	<u>$n\tau_c$ (cm⁻³/sec)</u>	<u>β</u>
End Plugs	4×10^{13}	13	0.27	-	-	0.1
Solenoid	2×10^{13}	0.25	-	8	1.4×10^{11}	0.2

Recent Progress

1. A stable tandem configuration has been generated on TMX for the full 25 msec of operation with solenoid betas as high as 20%.
2. Electrostatic plugging has been demonstrated on TMX.
3. TMX has shown improved electron confinement over 2XIIB with no apparent impurity problems.

Plans

TMX will be used to test concepts and ideas related to MFTF-B or TMR. A decision was made in January 1980 to modify TMX to permit testing the thermal barrier concepts.

Milestones

1. Submit report on measurements of initial electron beam experiments in TMX	May 1980
2. Begin plug optimization experiments (such as lower mirror ratio of the plug or larger plasma radius in the plug)	July 1980
3. Submit report evaluating impurities in TMX including types and origins of impurities	Oct. 1980
4. Obtain Thomson scattering measurements of TMX solenoid electron temperature	Oct. 1980
5. Begin ECRH heating of one end plug using one 200 kW gyrotron	Dec. 1980
6. Submit report on plug optimization experiments	Feb. 1981

Major Recent Publications

1. F. H. Coensgen, T. C. Simonen, and W. C. Turner, Tandem Mirror and Field Reversed Mirror Experiments, UCRL-82791, August 21, 1979.
2. F. H. Coensgen, et.al., "Electrostatic Plasma Confinement Experiments in a Tandem Mirror System", UCRL-83594, December 12, 1979.

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TANDEM MIRROR EXPERIMENT

LAWRENCE
LIVERMORE
LABORATORY
ATMXA

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Mirror Confinement Systems

Lawrence Livermore Laboratory (LLL)

Project

Beta II Experiment
W. Turner

OFE Contact

T. V. George

Purpose and Relationship to Other Projects

Beta II is a single cell minimum B magnetic mirror machine. The device was formerly (prior to June 1978) known as 2XIIB which successfully demonstrated neutral beam buildup and sustenance of mirror confined plasma. These achievements led to development of the tandem mirror experiment (TMX) now in operation and the MFTF experiment under construction at LLL. The main thrust of the current experimental program in Beta II is the development of a field reversed target plasma that can be trapped in a quasi-static mirror and sustained by neutral beam injection. If successful, this program would provide the data base for extrapolation to a field reversal experiment in the MFTF facility.

Approach

The approach being pursued on Beta II for production of field reversed plasma utilizes a magnetized coaxial plasma gun. A conventional coaxial gun is fitted with solenoidal coils along the inner and outer electrodes and immersed in an equilibrium guide field solenoid. The inside electrode solenoid generates the poloidal flux, and together with the guide field forms a magnetic cusp in front of the gun muzzle. The outside electrode solenoid controls the magnetic field between gun electrodes. When the accelerated plasma leaves the gun muzzle, the poloidal field lines become elongated and then reconnect to form closed field lines around the drifting ring. The gun is arranged to inject axially into the Beta II mirror. Field reversed plasma trapped in the mirror will be heated by 20 kV neutral beam injection.

Parameters

A. Machine:

Guide field: 6 kG.

Yin-yang field: 4 kG @ center, 9.7 kG @ mirror, 1.5m between mirrors.

Neutral Beams: 10 ea. 20 kV beams, 400 amps atom current @ plasma,
10 msec. duration.

Plasma gun: inner electrode diam. = 15cm; outer electrode diam. = 30cm;
electrode length = 150cm; 185 kJ capacitor bank;
 3.0×10^{13} kG - cm² inner solenoid flux.

B. Plasma (maximum achieved):

Mirror confined plasma: $\hat{n}_e \approx 10^{14}$ cm⁻³, $\bar{E}_i = 12$ keV, $T_e = 140$ eV,
 $\hat{\beta} \approx 1.0$, $\hat{n}\tau_E \approx 3 \times 10^{10}$ cm⁻³-sec.

Field reversed plasma: $\Delta B/B_0 \approx 3$ in 4.8 kG guide field; density,
temperature and confinement unknown.

Recent Progress

1. Completion of construction of magnetized coaxial plasma gun and routine operation of all components at design level.
2. Installation and debugging of magnetic probe diagnostics and computer data acquisition.
3. Production of field reversed plasma with $\Delta B/B_0 \approx 3$ in $B_0 \approx 4.8$ kG guide field.

Plans

Plasma gun production of field reversed plasma has been demonstrated. The next step is to translate and mirror trap the field reversed plasma. Diagnostic capability is being extended beyond the purely magnetic measurements to include measurements of density and temperature.

Milestones

1. Trap field reversed plasma rings in Beta II	June 1980
2. Submit report on injection and trapping of field reversed plasma rings	July 1980
3. Operate Beta II with industrial prototype MFTF startup plasma gun (in support of MFTF Project)	Aug. 1980
4. Begin neutral beam heating of trapped field reversed plasma rings	Sept. 1980
5. Achieve heating and sustaining of field reversed plasma rings	Nov. 1980
6. Submit report on initial results of heating and sustaining field reversed plasma rings	Feb. 1981

Major Recent Publications

1. W. C. Turner, C. W. Hartman, J. Taska, A. C. Smith, Jr., "Initial Results of Field Reversed Plasma Gun Experiment", Proceedings of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, NJ, December 12-14, 1979.
2. W. C. Turner, C. W. Hartman, J. W. Shearer, J. Taska, "Field-Reversed Plasma Gun Experiment", Bull. Am. Phys Soc., 24 1083, 1979.
3. J. L. Eddleman, C. W. Hartman, J. W. Shearer, W. C. Turner, "Magnetohydrodynamic Calculations of Coaxial Gun Production of Plasma", *ibid.*
4. J. W. Shearer, J. L. Eddleman, C. W. Hartman, W. C. Turner, "Field Line Reconnection in Coaxial Gun Produced Plasma", *ibid.*
5. D. S. Prono, B. W. Stallard, "Beta II Pulsed Ion Diode Facility and Experiments", *ibid.*

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BETA-II

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Mirror Confinement Systems

Lawrence Livermore Laboratory (LLL)

Project

Mirror Fusion Test Facility (MFTF)

K. Thomassen

OFE Contact

W. A. Marton, R. E. Price

Purpose and Relationship to Other Projects

MFTF is a large single cell Yin-yang mirror designed to advance the physics and technology of mirror reactors. Its principal physics goals are to explore the scaling relationships developed from theoretical and experimental investigations on 2XIIB. It extends the parameter range available in 2XIIB to reactor relevant regimes. Major technological advances are expected through constructing and operating a large superconducting magnet and the largest neutral beam system (150 MW) in the fusion program.

Approach

The machine is designed to contain a 50 keV plasma having a diameter of 13 ion gyroradii. Warm plasma stabilization of the drift cyclotron loss cone (DCLC) mode can then be achieved with less stream current than needed with smaller machines like 2XIIB. Higher electron temperature (approximately 1 keV) can therefore be expected, and with the higher ion temperatures provided by an 80 kV beam system, the confinement ($n\tau \sim 10^{12} \text{cm}^{-3}\text{-sec}$) should improve an order of magnitude over 2XIIB.

Technological advances are made using a 500 MJ superconducting magnet, a sustaining beam system with a 30 sec power supply and 0.5 sec source capability. Good vacuum conditions are to be maintained with approximately 1000 m² of liquid helium cooled cryopanel.

Parameters

A. Machine:

Magnet - 7.8T NbTi conductor, 2T @ center, 3.6m mirror to mirror.

Vessel - 35' dia., 59' length; 1000 m² cryopanel, 3000 W & He refrigerator.

Beam System - 156 MW beam input, 70 MW (max) neutral power @ 80 kV
for 0.5 sec.

Controls - touch panel control, fully computer interfaced.

B. Plasma (design objective):

$R_p = 30 \text{ cm}$, $L_p = 140 \text{ cm}$, $T_i = 50 \text{ keV}$, $T_e = 1 \text{ keV}$, $n\tau \sim 10^{12} \text{ cm}^{-3} \text{ sec}$,

$n \sim 10^{14} \text{ cm}^{-3}$.

Recent Progress

1. Magnet wound.
2. Vessel erected.
3. Control building complete, computers installed.
4. Beam accel supply--site construction complete, transformers being installed.

Plans

The four-year construction period began October 1978 and scheduled completion is September 1981. The FY 1980 decision to complete this machine as a tandem mirror (MFTF-B) has changed these plans as discussed in the description of the MFTF-B project.

Milestones

1. Complete winding of second superconducting coil	March 1980
2. Complete installation of 230 kV substation	Nov 1980
3. Complete construction of Building 441	Dec 1980
4. Complete installation/integration of sustaining neutral beam power supply system	Feb 1981
5. Complete installation and checkout of superconducting magnet system	June 1981
6. MFTF construction project completed and accepted by DOE	Sept 1981

Major Recent Publications

Numerous LLL and Engineering Conference Reports. No major journal articles.

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MIRROR FUSION TEST FACILITY

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Mirror Confinement Systems

Lawrence Livermore Laboratory (LLL)

Project

Mirror Fusion Test Facility - B (MFTF-B)
K. Thomassen

OFE Contact

W. A. Marton/R. E. Price

Purpose and Relationship to Other Projects

MFTF-B is a large tandem mirror facility designed for operation at reactor temperatures and potentials. The objectives include reaching confining potentials of approximately 40 keV, where $n\tau \sim 5 \times 10^{13} \text{ cm}^3 \text{ sec}$ and Q_{DT} approaching unity are expected. It is intended as the bridge for both physics and technology in developing the tandem mirror reactor concept from TMX to a DT burning Mirror Next Step (MNS).

Approach

To achieve the performance objectives and to demonstrate some of the large scale engineering requirements of MNS, MFTF-B extends the simple tandem mirror concept by incorporating thermal barriers. To do so, a C-coil is added at each end of the machine to produce a field peak outside of the Yin-yang plugs. The auxiliary cells (A-cells) so produced allow the creation of a barrier, and electron cyclotron heating then produces the large confinement potentials. The technologies are extended by MFTF-B through the use of a superconducting magnet set, and by operation of the machine for 30 sec pulses at a 10% duty cycle. This operation represents a major extension in both the vacuum and neutral beam technologies toward ultimate steady state reactor operations.

Parameters

A. Machine:

Superconducting magnets - 14 center cell coils (5 m bore), 2 transition coils, 2 Yin-yang pairs (360 ton each), 2 C-coils (200 ton each), total stored energy - 3000 MJ.

Overall length 62 meters.

Neutral beam (80 kV) power 150 MW.

ECRH power 1.6 MW.

B. Plasma (design objective):

Center cell: $T_i = 15 \text{ keV}$, $R_p = 54 \text{ cm}$, $n = 2 \times 10^{13} \text{ cm}^{-3}$, $\beta = 20\%$,
 $B = 0.5\text{--}1.0\text{T}$, $n\tau \sim 5 \times 10^{13} \text{ cm}^{-3} \text{ sec}$.

Plugs : $n = 6 \times 10^{13} \text{ cm}^{-3}$, $\beta = 40\%$, $B = 2\text{T}$, $n\tau = 1.0^{13} \text{ cm}^{-3} \text{ sec}$.

Recent Progress

1. Conceptual design completed December 1979.
2. Technical review, January 1980.
3. DOE approval, April 1980.

Plans

Following DOE approval of the conversion to MFTF-B, completion of the project is planned for the 1984-1985 time frame.

Milestones

1. Begin construction	April 1980
2. Complete construction	1984 - 1985

Major Recent Publications

MFTF-B Proposal (LLL Report in progress).

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Mirror Confinement Systems

University of Wisconsin

Project

Phaedrus Tandem Mirror Experiment (Phaedrus)
R. S. Post

OFE Contact

T. V. George

Purpose and Relationship to Other Projects

The Phaedrus device is a tandem mirror similar to but smaller than the TMX facility at LLL. It has the two-fold purpose of: (1) studying the effectiveness of ion cyclotron resonance heating as an auxiliary power source for driving the plugs, and (2) studying the physics of tandem mirror operation, particularly central cell confinement and transport. Studies of ion heating of decaying or neutral beam sustained plugs, electron heating, rf trapping, central cell ion heating, rf plugging and the usefulness of ICRF for microinstability control are expected to provide an additional data base, along with the TMX project, for the MFTF-B.

Approach

The basic approach is to test tandem mirror configurations utilizing rf heating in the end plugs in the ICRF range (fast and slow waves). The ambipolar potentials of the minimum-B mirror end plug plasmas will electrostatically confine plasma in the central cell. The end plugs will be sustained for the duration of the central cell confinement time by low energy neutral beam fueling and rf heating. The emphasis of the rf heating experiments is on rf coupling efficiency and better overall plasma power balance.

Parameters

A. Machine:

	Center Field	Axial Length	Plasma Radius	Pulse Length	Mirror Ratio
	B_o (kG)	L_m (m)	r (m)	(sec)	
End Plug	4	1	.07	1 msec gun	1.8
	1 sec.			plasma	
Solenoid	.2	4	.30	10 msec beam	36

B. Plasma (maximum achieved):

	n_i (cm ⁻³)	T_i (eV)	T_e (eV)	τ_c (msec)	β
End Plugs	7×10^{12}	2000	40	1	28%
Solenoid	2×10^{12}	15	40	11	3%

Recent Progress

1. Operation of a single end plug with plasma produced by Titanium washer guns.
2. Rf heating of minimum-B mirror end plug with the slow wave at ω_{ci} . Very efficient coupling to the plasma has been achieved with up to 100 kW of rf. This results in a doubling of the ion energy with no deleterious effects on plasma confinement.
3. Rf heating with the fast wave at $2\omega_{ci}$. For power levels up to 10 kW, efficient coupling is observed with some evidence of ion tail production.
4. Neutral beams have been tested at up to 4 amps extracted at 6 kV.

Plans

High power rf heating (200-400 kW) will be continued on both end plug plasmas. Neutral beams which extract ions at 6 keV energy are being developed for sustaining the plugs. The plug beam pulse time will exceed the central cell confinement time, permitting study of tandem mirror operation. Central cell rf heating is also planned to allow confinement studies at varying central cell collisionality. Thermal barrier physics studies will also be carried out.

Milestones

1. Accomplish plasma trapping studies in both end cells	April 1980
2. Initiate ICRF heating in both ends cells	April 1980
3. Submit report on central cell confinement experiments	Aug 1980
4. Shut down Phaedrus for thermal barrier modifications and/or installation of neutral beam line on second end cell	Aug 1980
5. Start up Phaedrus	Sept 1980
6. Submit report evaluating results of investigating NB fueled rf heated end plugs, microstability of plugs, operation of tandem mirror with thermal barrier, and physics of heat flux through thermal barrier	Feb 1981

Major Recent Publications

1. J. Kesner, "Quasi-Linear Model for Ion Cyclotron Heating of Tokamaks and Mirrors", Nuclear Fusion 18 (1978), 781.
2. J. Kesner, "ICRF Fueling of Tandem Mirror End Plugs", Nuclear Fusion 19 (1979), 107.
3. K. C. Shaing, J. Kesner, R. W. Conn, "The Interaction of a High Frequency Magnetic Field with the DCLC Instability", Phys. Fluids 22 (1979), 2940.
4. J. Kesner, "Passive Generation of Ambipolar Potential Barriers in a Tandem Mirror", Comments on Plasma Physics and Controlled Fusion (1979).
5. J. Kesner, "Axisymmetric Tandem Mirror Plugs", to be published in Nuclear Fusion (1980).

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Mirror Confinement Systems

TRW, Inc.

Project

Symmetric Tandem Mirror (STM)

N. H. Lazar, R. A. Dandl (Consultant)

OFE Contact

J. M. Turner

Purpose and Relationship to Other Projects

The STM facility will be used to examine the feasibility of applying high beta, hot electron diamagnetic plasmas, similar to EBT annuli, to stabilize a simple magnetic mirror configuration. The microwave, ECH techniques used for generation of the diamagnetic plasmas are similar to those used by R. A. Dandl in EBT-I. The diagnostic techniques are adapted from those in EBT, ELMO and Interem. If this stabilization mechanism proves to be feasible, a symmetric tandem mirror configuration will be constructed to investigate plasma potential control techniques which would be applicable in the larger mirror facilities such as TMX and MFTF-B.

Approach

Electron cyclotron heating (ECH) is used to produce and sustain high beta, hot-electron diamagnetic plasmas. Experiments with microwave heating in EBT and ELMO have demonstrated the formation of diamagnetic, hot electron annuli in the region near the magnetic midplane where the applied frequency is twice the electron cyclotron frequency. By using several neighboring microwave frequencies, the region where the second harmonic resonance occurs may be spread over the entire midplane. This technique is intended to control the size and examine the structure of the diamagnetic plasma volume. In follow-on experiments simple mirror cells may be added to either end of the existing facility. Energetic ion plasmas produced in these cells will simulate a tandem mirror configuration to permit potential control experiments.

Parameters

A. Machine:

<u>B(kg)</u>	<u>Mirror Ratio</u>	<u>Length</u>	<u>Plasma Diameter</u>	<u>Frequencies (GHz)</u>
5.0 (max)	2	75cm	30cm	8.0,9.2,9.5,10.0
	<u>Power (kW)</u>		<u>Experiment Duration</u>	
	2.5,1,1,3		cw	

B. Plasma (maximum achieved):

<u>n_e (Hot)</u>	<u>T_e (Hot)</u>	<u>Hot Plasma Volume</u>	<u>n_e (Cold)</u>	<u>T_e (Cold)</u>
10^{11} cm^{-3}	100 keV	~5 liters	$\sim 10^{11} \text{ cm}^{-3}$	~ 30 eV
	<u>Volume</u>		<u>T_i (Cold)</u>	
	~10 liters		< 5 eV	

Recent Progress (New Project)

1. The facility is presently being completed and initial heating experiments were begun December 1979.

Plans

Detailed structure of the diamagnetic plasmas produced in the STM facility will be examined. Ion heating techniques will be examined for implementation in the follow-on experiments anticipated for the tandem mirror configuration.

Milestones

1. OFE conducts review of the preliminary STM data	March 1980
2. Initiate experiments to examine stability boundaries as a function of plasma parameters	April 1980
3. Initiate detailed design of tandem three-cell facility for Phase II	April 1980
4. Complete detailed design of tandem three-cell facility for Phase II	Sept 1980
5. Measure the spatial distribution of plasma pressure and diamagnetism	Sept 1980
6. OFE review of Phase I and decision on whether to proceed with Phase II	Sept 1980

Major Recent Publications (New Project)

None.

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STM

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Mirror Confinement Systems

Los Alamos Scientific Laboratory (LASL)

Project

Field Reversal Experiments (FRX-A and FRX-B)

R. K. Linford (Project Leader), A. R. Sherwood, R. E. Siemon

OFE Contact

T. V. George

Purpose and Relationship to Other Projects

The purpose of the FRX line of experiments is to study the formation, stability, and transport properties of Compact Tori without toroidal field, i.e., Field Reversed Configurations (FRC) for use as target plasmas in field reversal mirror reactors. The near term objectives of the FRX-A and FRX-B experiments are: (1) to develop FRC formation techniques that are compatible with translating and trapping FRC's, (2) demonstrate translation and trapping, and (3) study the equilibrium, stability, and transport of the trapped plasma.

Approach

FRX-A and B have both successfully produced FRC's using the usual field reversed theta pinch approach. The required pulsed-gas fill and preionization techniques are being developed in FRX-A. The FRX-B has been modified to attempt the production of longer-lived FRC's using the barrier field approach of Kurtmullaev, with reconnection controlled by driven mirror and cusp coils. Successful study of a long lived trapped target requires that the FRC plasma be transported to a vacuum region. This is to be accomplished by the addition of quasi-steady state field coils for translating and trapping the plasma and extension of the vacuum system.

Parameters

Machine:	Coil		B(kG)	τ_r (μ s)	$\tau_{L/R}$ (μ s)
	Length(cm)	Diameter(cm)			
FRX-A	90	25	6	3.2	
FRX-B (old)	100	25	9	2.4	150
FRX-B (new)	100	22	12	3.0	130

B. Plasma (FRX-B old):

Fill Pressure (mTorr, D_2)	$n_{\max}$ (10^{15} cm^{-3})	T_e (eV)	T_i (eV)	τ_E (μ s)
5	1	150	>800	<10
17	3	130	200	~35

Recent Progress

1. Thomson scattering was used to determine $T_e \sim 130$ eV inside the separatrix with very little spatial or temporal variation before the FRC was destroyed by the rotational instability (up to 50 μ s). Outside the separatrix T_e dropped from 100 eV to about 10 eV within 30 μ s. These results support the existence of closed field lines inside the separatrix.
2. The estimated particle loss based on various diagnostics was 45% at the outset of the rotational instability and it is consistent with present theoretical understanding.
3. The pressure balance was confirmed between the plasma and supporting poloidal field within the cumulative error ($\sim 40\%$). This result is consistent with the assumption that no toroidal field exists in the FRC.

Plans

The results of the barrier field and controlled reconnection studies will be compared with the initial FRX-C results to help decide whether to convert FRX-C to the Kurtmullaev mode of operation. The FRX-C will be used to inject an FRC plasma into the dc field of the Compact Torus Experiment (CTX) trapping facility.

Milestones

1. Report initial results of multipole barrier field studies on FRX-B March 1980
2. Initiate modification of FRX-B with cusp/mirror reconnection system March 1980
3. Complete and test modification of FRX-B with cusp/mirror system April 1980
4. Report initial results of reconnection studies on FRX-B June 1980
5. Initiate modification of FRX-B for plasma translation experiment June 1980
6. Complete and test modification of FRX-B with translation system Aug 1980

Major Recent Publications

1. W. T. Armstrong, R. K. Linford, J. Lipson, D. A. Platts, E. G. Sherwood, "Status of Field Reversed Experiments (FRX)", in Conf. Record of IEEE, 1979 Conf. on Plasma Science, Montreal, p. 141.
2. W. T. Armstrong, R. K. Linford, J. Lipson, D. A. Platts, E. G. Sherwood, "Diagnostic Systems in FRX", in Conf. Record of IEEE, 1979 Conf. on Plasma Science, Montreal, p. 144.
3. W. T. Armstrong, R. K. Linford, J. Lipson, D. A. Platts, E. G. Sherwood, "Field Reversal Experiments", in Proc. IX European Conf. on Controlled Fusion and Plasma Physics, Culham, 1979.

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Mirror Confinement Systems

Massachusetts Institute of Technology (MIT)

Project

Constance II - Hot Electron Stabilization of DCLC
L. D. Smullin

OFE Contact

T. V. George

Purpose and Relationship to Other Projects

Constance II is a relatively small mirror facility having separately controllable solenoidal and multipolar fields. Its primary purpose is to study the suppression of DCLC instability. These techniques may be adopted on the MFTF, TMX, or other large scale mirror systems.

Approach

The basic approach of suppressing DCLC instability is by means of hot electrons produced either by electron beam plasma interaction (BPI) or by electron cyclotron resonance heating (ECRH).

Constance II is a relatively flexible machine that can be rather easily modified (for example, it will be possible to replace the 4-pole Ioffe bar coil set by a 6-pole set, in about 1 week). The plasma to be studied is injected from a T₁-washer plasma gun. The mirror trapped plasma reaches densities of $n \sim 10^{13}/\text{cc}$, and ion temperature $T_i \sim 200\text{-}300\text{ eV}$ are observed. Under proper vacuum conditions, achieved by gettering, a DCLC instability is observed. The principal experiment is to observe the variation of the DCLC oscillation intensity as a result of the beam plasma interaction and of the ECRH.

A secondary goal is to study the general behavior of a mirror trapped plasma under varying ratios of the 4-pole or 6-pole field to the mirror field.

Parameters

A. Machine: Mirror chamber 15" dia. x 70" long; Diameter of inside Ioffe bars 9"

Mirror field: $B_{\max} = 10 \text{ kG}$, $B_{\max}/B_{\min} = 2$, mirror length .9 m

Quadrupole field: $0 < NI \lesssim 80000$ amp turns, can achieve full min-B configuration for $B_{\min} = 5 \text{ kG}$

Guide field for plasma stream 2.4 m long. $0 < B_g < 2 \text{ kG}$ (will be upgraded to $\sim 3 \text{ kG}$).

B. Plasma (maximum achieved):

Plasma gun injection pulse $0 < t < 1.5 \text{ msec}$ (.5 msec typical), 2000 amps arc current.

Mirror plasma: $n \approx 10^{13}/\text{cc}$, $T_i \approx 300 \text{ eV}$, $T_e \approx 10 \text{ eV}$.

Recent Progress

1. The 4-pole Ioffe bars have been installed and tested. Preliminary measurements of the mirror trapped plasma have been made with fixed mirror field and varying 4-pole field. The energy of the trapped plasma increased about 5 times when the 4-pole field configuration predicted marginal MHD stability.
2. A crude divertor coil was placed in the guide field region adjacent to the main mirror (similar to Kanaev's PR-6 experiment). The coil was energized following the plasma turn off to prevent the continued cold plasma flow. This has resulted in the density confinement time increasing by almost an order of magnitude to about the energy confinement time (100 μsec).

Plans

Constance II will be primarily devoted to hot electron stabilization of DCLC during FY 1980. Both ECRH and electron beam systems will be studied.

Milestones

1. Complete e-beam stabilization studies for a range of injection parameters, and submit report	March 1980
2. Submit report on hot electron stabilization of DCLC mode	March 1980
3. Evaluate results and submit proposed experimental program plan	April 1980

Major Recent Publications

None.

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CONSTANCE II

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Mirror Confinement Systems

United Technologies Research Center (UTRC)

Project

Plasma Stabilization Experiment (PSX)
E. A. Sziklas

OFE Contact

M. Johnson/T. V. George

Purpose and Relationship to Other Projects

PSX is intended to study rf plugging as a means for stabilizing the drift cyclotron loss cone (DCLC) mode in mirror confined plasmas without the attendant energy drain associated with the streaming plasma stabilization techniques demonstrated previously on 2XII-B. The results could impact the operation and performance of TMX and MFTF. The use of rf also has potential application for plugging mirror throats and for generating thermal barriers in tandem mirror reactors.

Approach

An isolated mirror confined plasma, which is expected to be DCLC unstable, is produced by trapping a gun injected plasma in a minimum-B coil. Rf fields are applied to the plasma in the vicinity of the mirror throats at a frequency near the local ion cyclotron frequency. The presence of rf should generate a pondermotive potential barrier which will adiabatically reflect untrapped cold ions back into the containment region. The resultant enhanced cold-ion density should stabilize the DCLC mode by the partial filling of the ion loss cone.

Parameters

- A. Machine: Baseball magnet
Distance between mirrors: 30 cm
Center field strength: < 15 kG
Mirror ratio: 2
Plasma source: hydrogenated titanium washer gun
- B. Plasma (maximum achieved): Peak plasma density: $\sim 5 \times 10^{12} \text{ cm}^{-3}$
 $T_e \sim 10 \text{ eV}$
 $T_i \sim 100 \text{ eV}$
 $\beta < 1$
Plasma lifetime, $\tau \sim 200 \mu\text{s}$

Recent Progress

1. Nagoya-type III antennas have been designed and installed in the UTRC mirror facility.
2. Radiofrequency fields have been applied to a mirror confined plasma.
3. Preliminary results give indication of a stoppering effect (reduced end loss), an electron heating effect, and plasma dumping.

Plans

Continue application of rf fields to define in quantitative terms: (1) the magnitude of the electron temperature rise, (2) the conditions under which stoppering and/or plasma dumping occur, and (3) the effect of rf on plasma stability.

Milestones

1. Complete ICRF stabilization experiments and complete final report April 1980
2. OFE review of UTRC progress and future plans April 1980

Major Recent Publications

1. Plasma Stabilization Experiment, E. A. Sziklas, W. J. Fader, R. A. Jong, D. H. Polk, and J. H. Stufflebeam, DOE/ET/53087-1, October 1979.

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Mirror Confinement Systems

Oak Ridge National Laboratory (ORNL)

Project

Elmo Bumpy Torus - Scale (EBT-S)
J. Sheffield, R. Colchin, G. Haste

OFE Contact

J. M. Turner

Purpose and Relationship to Other Projects

EBT is a toroidally linked mirror system which possesses several attractive features including: steady state operation, potential for high beta containment, favorable scaling to a reactor, and possibilities of many auxiliary heating approaches. EBT-S is an upgrade in magnetic field strength of the original EBT-I experiment. Its purpose is two-fold: first, to test the validity of scaling laws for hotter, denser plasma conditions; and second, to serve as a test bed for methods, techniques, and prototype hardware which is being considered for the EBT proof-of-principle experiment, EBT-P.

Approach

EBT uses microwave power for creating, heating, and stabilizing (by means of hot electron rings) the plasma in the bumpy torus configuration. The density, temperature, and lifetime of the plasma are observed to depend on the frequency and power of the applied microwaves. Extension of these scaling laws are to be tested with newly developed gyrotron sources of higher rf frequency and power level. Supplementary ion heating at the ion cyclotron frequency will be used to establish a finite beta toroidal core plasma.

Parameters

A. Machine:

$B_{res} = 10 \text{ kG (28 GHz)}$
 $R = 1.5 \text{ m}$
 $r = 0.1 \text{ m (mirror throat)}$

ECRH Power

10.6 GHz: 30 kW
18 GHz: 50 kW
28 GHz: $\geq 50 \text{ kW}$

B. Plasma (operating range):

$$n_e = 1.5 - 0.6 \times 10^{12} \text{ cm}^{-3}$$

$$T_e = 100 - 500 \text{ eV}$$

$$T_i = 50 - 150 \text{ eV}$$

$$\tau_e = 2 - 7 \text{ ms}$$

Recent Progress

1. Operation with 28 GHz gyrotron power at 50 kW.
2. Installation and operation of a Thomson scattering system with scanning capability.
3. Data survey of $n_e \tau$ and stored energy as a function of pressure and microwave power to delineate various operational mode boundaries.
4. Increased capability of several diagnostics, including the ion beam probe and five-channel soft x-ray systems.

Plans

1. Add scanning capability to present diagnostic systems.
2. Determine scaling information as a function of frequency.
3. Test ICRH heating.
4. Increase the ECR power available.

Milestones

1. Award contract to industry for divertor studies March 1980
2. Begin ICRH experiments in support of EBT-P (heating) April 1980
3. Evaluate design for split mirror magnetic configuration April 1980
4. Begin ARE coil fabrication (six months are needed to fabricate 48 coils) May 1980
5. Begin fabrication of split mirror coils June 1980
6. Review by Panel of the results of ICRH and plasma parameter scaling with μ -wave frequency and power, and submit written report March 1981

Major Recent Publications

1. J. A. Cobble and J. C. Glowienka, "Optical Diagnostics Using a Barium Ion Beam for Spatial Resolution of Plasma Parameters," (ORNL/TM6785, March 1979), IEEE Trans. on Plasma Science, Vol. PS-7, No. 3, September 1979, p. 14.
2. N. H. Lazar and K. H. Carpenter, ORNL; J. M. Tyson, E.S. Warden, and H. W. Moos, JHU, "Spatial Distribution of Impurities and H Neutrals in Elmo Bumpy Torus (EBT)," Nucl. Fusion 19(5), 571 (1979).
3. F. W. Baity, K. H. Carpenter, J. A. Cobble, R. J. Colshin, H. O. Eason, J. C. Glowienka, G. R. Haste, C. L. Hedrick, E. F. Jaeger, R. K. Richards, T. Uckan, and T. L. White, ORNL; F. M. Bieniosek, K. A. Connor, R. L. Hickok, and S. P. Kuo, RPI, Troy, NY; R. A. Dandl, Consultant at General Atomic Co., San Diego, CA; S. Hiroe, IPP, Nagoya, Japan; and N. H. Lazar and B. H. Quon, TRW, Redondo Beach, CA; "Scaling in Elmo Bumpy Torus (EBT)," 9th Conf. on Controlled Fusion and Plasma Phys., Oxford, England, September 17-21, 1979, Paper A2.1.
4. P. L. Colestock, K. A. Connor, and R. L. Hickok, Rensselaer Polytechnic Inst.; and R. A. Dandl, ORNL; "Direct Measurement of Plasma Space Potential on Elmo Bumpy Torus," Phys. Rev. Lett. 40(26), 1717 (1978).
5. H. Ikegami (IPP) and R. A. Dandl (ORNL), "Electron Cyclotron Heating in Bumpy Torus Program," Joint Varenna-Grenoble Intern. Symposium on Heating in Toroidal Plasmas, Grenoble, France, July 3-7, 1978, Proc. Conf. Heating in Toroidal Plasmas, Vol. II, 321 (1978).
6. EBT Experimental Group, EBT Theory Groups, with support from the UV Spectroscopy Group, and Heavy Ion Beam Group, "Experimental and Theoretical Studies of the Elmo Bumpy Torus (EBT)," Seventh Intern. Conf. on Plasma Phys. and Cont. Nucl. Fusion Research, Vol. II, p. 365, IAEA, Vienna (1979).

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Mirror Confinement Systems

Site to be selected.

Project

Elmo Bumpy Torus Proof-of-Principle Experiment (EBT-P)
A. L. Boch, J. Sheffield

OFE Contact

J. M. Turner

Purpose and Relationship to Other Projects

The purpose of EBT-P is to extend the scientific data base and significantly advance the EBT concept as an alternative to the tokamak and mirror approaches to a fusion power reactor. EBT-P will be a significant scale-up from the current EBT-I/S experiment to provide a higher density, higher temperature proof-of-principle extension of the EBT concept that can be extrapolated to the reactor plasma regime. Important specific objectives are to:

- Determine whether energy confinement of the core plasma is sufficient to make a viable D-T burning device.
- Determine whether there is a favorable power balance in the relativistic electron annuli at betas that are sufficient to stabilize the core plasma in a reactor.
- Advance technology in the application of high-power microwave heating toward the higher frequency that will be required for a reactor.

Approach

As a proof-of-principle experiment, EBT-P will be designed for steady state operation with near reactor machine parameters. The facility therefore calls for superconducting magnets for confinement of plasma generated with ECRH at 60 GHz and upgrade capability 90 GHz. Core beta of 5% is to be realized with supplementary ICRH, defined as the midplane plasma pressure to the magnetic pressure outside the ring. The project has been identified to involve industry in a major role in all phases from project definition through operation. ORNL is managing the EBT-P project and has obtained broad industrial participation in project definition studies leading to a proposed reference design for EBT-P. Based on the proposed design, DOE/OFE with assistance from the technical community will review the project and reassess the EBT program. Assuming a decision to continue the project, the approved reference design will be used by ORNL as a basis for soliciting proposals and selecting a primary industrial participant (IP) who will design and build EBT-P (Phase II) and have a major role in its operation (Phase III). The site will be selected by DOE with benefit of industry proposals and ORNL evaluation.

Parameters

		<u>Initial</u>	<u>Maximum</u>
A. Machine:			
Major radius, R (m)		4.5	4.5
Mean plasma radius, $\bar{a}$ (m)		0.17	0.17
Mechanical aspect ratio, A		15.5	15.5
Number of coils		36.0	36.0
Maximum field, B max (T)		5.6	7.4
Resonant field, B _r (T)		2.1	3.2
Microwave frequency (GHz)		60/28	90.0
Mirror ratio, M		2.2	2.2
B. Plasma (design objective):			
	<u>Initial</u>	<u>Maximum</u>	<u>With Improvements</u>
n _e (cm ⁻³)	1.7 x 10 ¹³	3.8 x 10 ¹³	~ 5 x 10 ¹³
T _e (keV)	2.0	3.3	~5
T _i (keV)	0.4	0.7	~2
β at midplane axis (%)	0.5	0.9	~2
τ (s)	3 x 10 ⁻²	3 x 10 ⁻²	~ 1 x 10 ⁻¹
nτ (cm ⁻³ s)	5 x 10 ¹¹	1 x 10 ¹²	~ 5 x 10 ¹²
T _R (MeV)	~0.5	>0.5	

Recent Progress

1. Four industrial teams and ORNL completed independent project definition studies and reference designs.
2. A proposed reference design for EBT-P was developed to meet proof-of-principle goals and perceived schedule and budget requirements.
3. The proposed reference design and project plans were presented to the EBT-P Review Panel convened by DOE.
4. Final reference design established by OFE and project continuation approved.
5. ORNL released Phase II (Design, Fabrication, and Installation) RFP.

Plans

EBT-P will be designed and built so that in its initial operation it will be able to achieve a significant advance over EBT-I/S and satisfy the scaling requirements of proof-of-principle. The device will be constructed to offer the greatest possible flexibility for improvements which may be expected to improve the performance. For example, it is proposed that EBT-P start operation at 60 GHz as determined by realistically expected advances in microwave source technology, but the magnets will have the capability to accommodate 90 GHz microwave sources which are being developed. This increase in frequency with appropriate ring and heating power should lead to a factor of about 2 improvement in $n\tau$. Other potential improvements are planned and will be added as experimental results indicate.

Milestones

1. ORNL completes Phase II selections	April 1980
2. DOE site determination	May 1980
3. Union Carbide Corp., Nuclear Division, authorizes Industrial Participant to start work	June 1980

Major Recent Publications

1. "EBT-P Proposed Reference Design Report," A. L. Boch (Project Manager), ORNL/TM-7191, January 1980.

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