CONF-880406--113

UCRL-88950
PREPRINT

UCRL--88950

DE84 002783

THE MIRROR FUSION TEST FACILITY:
AN INTERMEDIATE DEVICE TO A MIRROR FUSION REACTOR

Victor N. Karpenko

This paper was prepared for submittal to the 5th
Topical Meeting on the Technology of Fusion
Energy, Hilton-Knoxville and Holiday Inn-World's
Fair, Knoxville, TN, 4/26-28/83.

March 30, 1983

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THE MIRROR FUSION TEST FACILITY:
AN INTERMEDIATE DEVICE TO A MIRROR FUSION REACTOR

V. N. KARPENKO
Lawrence Livermore National Laboratory, University of California
P. O. Box 5511/L-636
Livermore, California 94550
(415) 422-9973

ABSTRACT

The Mirror Fusion Test Facility (MFTF-B) now under construction at Lawrence Livermore National Laboratory represents more than an order-of-magnitude step from earlier magnetic-mirror experiments toward a future mirror fusion reactor. In fact, when the device begins operating in 1986, the Lawson criteria of

$$n\tau = 10^{14} \text{ cm}^{-3} \cdot \text{s}$$

will almost be achieved for D-T equivalent operation, thus signifying scientific breakeven. Major steps have been taken to develop MFTF-B technologies for tandem mirrors. Steady-state, high-field, superconducting magnets at reactor-relevant scales are used in the machine. The 30-s beam pulses, ECRH, and ICRH will also introduce steady-state technologies in those systems.

INTRODUCTION

In 1976, design of a large, single-mirror, magnetic fusion experiment was initiated at Lawrence Livermore National Laboratory (LLNL) in Livermore, California. This Mirror Experiment (MX) became the Mirror Fusion Test Facility (MFTF) with start of construction in October 1977. In 1980, results from the tandem Mirror Experiment (TMX) were so promising that the MFTF Project was upgraded to MFTF-B,¹ a large tandem-mirror device. After two years of physics and engineering alternative concept studies, the MFTF-B has been reconfigured to the axicell magnet array (Fig. 1).² This new axicell design more closely matches the future Mirror Advanced Reactor Study (MARS) configuration.³

In its current configuration MFTF-B has the capability of operating very near the scientific breakeven point for deuterium and tritium (D-T) fuel: plasma energy gain, or Q , ≈ 1 . Thus, it is a driven experiment with fusion energy output from the plasma comparable to the heating input to the plasma. Since only deuterium is to be used in MFTF-B, the experiment will actually demonstrate D-T equivalent performance in the range of $0.5 < Q < 1$. In addition, the 58-m-long device will provide the plasma scaling necessary to confirm theory regarding improved stability and reduced radial transport losses.

GOALS

The major physics goal of MFTF-B is to reduce end losses and thus accomplish confinement in the central cell that would approach "energy breakeven" in an equivalent D-T plasma. To do this, MFTF-B must:

1. Achieve axial ion-confinement times in excess of 1 s (axial $n\tau_c = 5 \times 10^{13} \text{ cm}^{-3} \cdot \text{s}$).
2. Generate maximum central-cell ion confining potentials ($\phi_c \approx 30 \text{ kV}$) sufficient for confinement, equivalent to achieving $Q \approx 0.5$ with D-T.
3. Achieve plasma temperatures sufficiently high to test the physics of both thermal barriers and radial transport in appropriate collisionless reactor regimes.
4. Demonstrate high-beta magnetohydrodynamic (MHD) equilibrium and stability ($\beta_c \approx 0.5$).
5. Achieve microstable sloshing ions and thermal barriers in the MFTF-B yin-yang magnets based on theoretical models.

The Axicell MFTF-B outperforms previous designs because it produces equivalent values of $n\tau_c$, T_{ic} , and T_{ec} at a much higher density in the

central cell and hence, yields a much higher fusion-power output per unit volume (Table I). It is this latter property, traceable to the high magnetic fields possible with the circular axicell coils, that is so attractive for a reactor.

PHYSICAL DESCRIPTION AND MACHINE LAYOUT

The MFIF-B device must provide a magnetic field in various regions of the vacuum vessel adequate to support plasma confinement. However, the MHD stability and adiabaticity requirements set limits on the magnet array and so provide the basic criteria. The specifics of the magnets, vacuum vessel, cryogenics, neutral beams, both the ion-cyclotron resonant heating (ICRH) and electron-cyclotron resonant heating (ECRH) systems, and the computer controls also define the experimental plasma confinement capabilities. Auxiliary components are attached to the vessel to startup, fuel, diagnose, and support varied experimental shots (Fig. 1).

Magnet Configuration and Tasks

The present configuration measures 58 m in length, including two 17-m-long stainless-steel end vessels (10.8-m in diam) and a 25-m central cell vessel (8-m in diam). Each end vessel contains a yin-yang anchor magnet with the individual coil centers 40 m apart (Fig. 2).

Within the vessel is a magnet array of 26 superconducting coils (shown in Fig. 3) configured into

- Two yin-yang anchor magnets of two coils each;
- Two transition quadrupole C-coils to the inner side of each yin-yang;
- Two high-field circular axicell magnets [three coils in each axicell: two 6-T coils and one insert of niobium-tin (Nb_3Sn) to provide 12 T on-axis] between the transition and central cell regions;
- Twelve 5-m-diam. solenoidal coils in the central region.

All of the coils except the inserts are composed of niobium-titanium (NbTi) superconductors.

Each of the coils is maintained in liquid helium at 4.5 K. Cooling will be by natural convective flow. The conductor will be cryostatically stabilized with enough copper to maintain surface heat flux below the critical level.

The yin-yangs will anchor the plasma against MHD instabilities, achieving confinement principally through the 12-T magnets on the outer side of the axicells. The principal confinement time for fusion reactions occurs in the central cell with spiraling deuterium ions bouncing back-and-forth between the inner axicell magnets at the 6-T point.

Figure 4 shows the magnetic field related to the magnet coils and vessel locations. The primary experimental mode is the MARS reference mode; the Technology Demonstration Facility or TDF (Kelley) mode is an alternate. Also illustrated are potential ϕ and density n , shown as a function of axial position relative to the center of the vessel; these depict the plasma confinement modes most related to advanced reactor concepts. Note also that the thermal barriers peak in the axicell and the anchor regions to help ion confinement.

Vacuum Conditions

The plasma internal pressure is established by densities from 2×10^7 to 5×10^9 particles per cubic centimeter. The end cell background pressure has a base value of 10^{-8} Torr but rises to 10^{-6} Torr during experimental operations. The vacuum system features high-volume cryocondensing pumps with 1500 m^2 of 4.5-K surfaces to pump all condensable gases and cryosorption pumps with 2.7-K surfaces on which argon is condensed to pump helium. The cryopanel are regenerated periodically.

Plasma Heating

During an experimental plasma shot, plasma-streaming guns on each end dome provide a target plasma for neutral-beam charge-exchange or ionization capture along the magnetic field lines.

The MFTF-B central cell has ten 80-kV, 80-A, 0.5-s neutral beams to provide added gas density. The 400-kW central plasma heating is achieved through ICRH at frequencies of 12 to 20 MHz, centered at 17 MHz on the ion second-harmonic frequency for I-T fields. Specifically, the machine runs at durations up to 30 s with six 80-kV, 35-A and two 40-kV, 50-A neutral-beam injectors to fuel, heat, and pump various regions of the confined plasma. The 80-kV high-energy pump beams (HEPB) are aimed axially from each end dome, whereas the 40-kV passing-particle barrier beams (P2B2), located one on each dome, are aimed 15° from the axis into each transition region. To raise the electron temperature in each yin-yang anchor and thus minimize ion cooling, ECRH is used at frequencies of 28, 35, and 56 GHz; eight 200-kW gyrotrons will be required. In addition, a closed-loop-feedback control system is incorporated in the ECRH system to allow for individual, simultaneous, or staggered operation of these eight gyrotrons. This flexibility of operation permits the complex spatial and temporal applications of ECRH needed to satisfy the requirements necessary for a wide range of plasma-physics experiments.

There are two 80-kV, 0.5-s beams in each yin-yang region plus a 30-s, 80-kV beam. In each axicell there is one 30-s, 80-kV beam and one 80-kV, 0.5-s beam. All beams except the 0.5-s beams in the yin-yang region are housed in external beamlines equipped with magnetic shielding, cryopanel, and ion dumps. The ion dumps will be capable of handling power fluxes up to approximately 5 kW/cm^2 on the surface perpendicular to the beam axis. There are also titanium getters that sublime 3 to 5 monolayers of titanium atoms onto the warm liners, or first walls, nearest the plasma. The gettered walls pump cold gas to reduce particle reflux and so reduce plasma heat loss during startup.

The absorbed heat is removed during each shot by cooling water in the high temperature beam dumps and warm liners. Liquid-nitrogen shields (at 80-85 K) protect the 4.5-K magnets and the 4.7-K cryopanel. For 4.35-K liquid helium, a 10-kW cryogenic helium refrigerator/ liquefier is used. There is also a 500-kW, liquid-nitrogen, closed-loop system to provide reliquefaction of nitrogen for cooling.

Diagnostics and Machine Control

The MFTF-B computer system is housed in a separate building hundreds of feet from the actual machine. Following an experimental shot, both the machine and plasma diagnostics data are sent through the computer system shared memory to the distributed data base in the nine supervisory computers, including two diagnostic data processing minicomputers. The operation is verified and data transferred between shots; this can occur as frequently as once every five minutes.

The plasma diagnostics measure the specific plasma parameters, determine energy balance, monitor densities, measure potential profiles, monitor plasma-wall interactions, determine particle and power flows, and characterize the plasma buildup in various regions. The initial diagnostics set will consist of 11 instruments with 130 data channels.

All the systems are operated by an hierarchical control and data handling system (Fig. 5). The system is projected to collect 8×10^6 bytes of data per shot. Seven consoles are included--five for subsystems, one for injectors, and one for the overall systems operation. All control functions

are directed and executed through touch panels on the operating console. The subsystem diagram with control blocks is displayed; then all levels are adjusted, switches are thrown, and ranges set from the control touch panels.

The supervisory minicomputers interface with local control computers through a 1-mega-byte shared memory. The local control computers (LSI-11) communicate through fiber-optic links to Computer-Automated Measurement and Control (CANAC) crates for local control, monitoring, and data communication. There are 85 subsystems to handle 35,000 diverse devices. The parameters are set before each shot, verified back to the systems control console, and time-sequenced for each element before the shot is initiated by the 3-MHz master timer.

Development Tasks for Completion

Completion of MFTF-B depends on the successful accomplishment of the development program. Critical items in this program are long-pulse neutral beams, gyrotrons, and high-field (12-T) Nb_3Sn coils. At this time, it appears that the development efforts currently underway will produce the desired results.

TECHNOLOGY DEMONSTRATED

By the end of 1981, construction of the original single-cell mirror machine (MFTF) had progressed substantially to allow integrated tests of several key systems as well as specific technology demonstrations.

Fabrication of MFTF-B additions was to begin in early 1982. This series of MFTF system tests was formulated to provide the principal data necessary to confirm the technology objectives of MFT⁺ and MFTF-B. At the cornerstone of the major Technology Demonstration was the 500-MJ yin-yang magnet test. The magnet operated at its full design current of 5775 A; the peak fields, case stresses, and conductor strains matched their calculated values very accurately.

For testing, the liquid helium required to cool the magnets was supplied by the 3075-W helium refrigerator; this device can produce helium at a rate of over 600 liters per hour. For the Technology Demonstration, the refrigeration plant operated reliably 24 hours a day, 7 days a week, for over 5 consecutive weeks.

During checkout of the external and internal vacuum systems, vacuum pressures of 10^{-8} Torr were achieved. (The vacuum systems employ both liquid helium and liquid nitrogen to achieve the low vacuum pressure demanded in a large vessel.) Also meeting test objectives were the system cryopanel; while maintaining a hard vacuum, they were able to pump added deuterium (heavy hydrogen gas) from the vessel housing the magnet.

Tests of the Supervisory Control and Diagnostic System (SCDS) were successful in validating the hierarchical structuring of controls and data handling from the machine's local control panels to the SCDS for operating and monitoring. The SCDS was used to test the operation of all the integrated test systems.

The production unit of an 80-kV, 80-A, 0.5-s neutral-beam source module was also successfully tested on the high-voltage test stand. These integrated

Tests provided a valuable database for critical review of various project management methods and techniques including quality assurance and safety programs. Tests of the neutral beams and their power supply will be accomplished in FY83.

MAINTENANCE AND OPERATION

The facility is designed to operate on a 10% duty cycle. Experimental pulses will be up to 30-s long every 5 minutes. Two experimental shifts are envisioned for each operating day plus one maintenance shift. Because of high-neutron production, the full-performance shots will be limited to 2000 to 3000 s/wk. The neutrons produced by the plasma during operations will penetrate everywhere within the vault. However, because there are few neutron absorbers within the vault, most of the neutrons will undergo a large number of scattering collisions during their lifetimes. The resulting neutron flux external to the vacuum vessel has a magnitude of approximately 4×10^8 n/cm² per second of plasma operation. The neutrons range in energy from 2.5 MeV to thermal, but generally average about 50 keV. The actual energy spectrum of the neutron flux varies considerably from place to place outside the vessel, but the total flux is approximately uniform. Inside the vacuum vessel, the expected neutron flux ranges up to 2×10^{11} n/cm²·s near the axicell magnets.⁴ Contact maintenance is permitted 2.5 hrs after device shutdown at the vessel boundary, but personnel are not permitted in the vault during device operation.

The selection, whenever possible, of long lifetime components, modular construction, and opportunistic replacement is geared to minimize downtime for maintenance.⁵

Since MFTF-B will be an assemblage of many independent subsystems, its Availability is the product of the Availabilities of all the subsystems. Hence, each of the subsystems must be extremely reliable to reach the goal of 70% overall Availability. Both LLNL and its contractors apply design principles for Availability to each component and subsystem. Figure 6 shows schematically how the concept of planned Availability applies to the stages of the project.

BUDGET AND SCHEDULE

The budget for MFTF-B consists of two elements: design and construction of the facility (\$243.2 M) and operating funds (\$161.4 M), which include research and development, experimental auxiliary components, spare parts, and diagnostic devices. The change to the improved axicell configuration did not increase the overall cost of the project. As of February 1983, the current status indicates that 66% of construction has been accomplished against a completion date of September 1985. The operating funded activities are 32% accomplished with operational readiness targeted for June 1986.

Since the MFTF construction project started in October 1977, LLNL has pursued a policy of involving industrial partners as extensively as possible. Currently about 85% of the construction project money has been placed with industry, primarily in the form of performance contracts including design, construction, and testing of major systems and components. An additional step has recently been incorporated; LLNL and industry will participate in a cost-sharing development program for the plasma heating and diagnostics

systems for MFTF. These efforts will expand industrial capability as well as allow the industrial partner to gain direct experience in the operational aspects of fusion by performing the integration and test operations of the components.

The Axicell MFTF-B focuses the experimental mirror fusion program on an attractive reactor concept that will remain the center of reactor studies and program planning for the next several years. At the same time there is sufficient flexibility for continued innovative improvement, as has been characteristic of the tandem mirror program in the past.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

REFERENCES

1. K. I. THOMASSEN and V. N. KARPENKO, Tandem Mirror Fusion Test Facility-MFTF-B Conceptual Design Report and Project Proposal, Lawrence Livermore National Laboratory, Livermore, CA, Rept. LLL-PROP-163, Rev. 1 (1980).
2. K. I. THOMASSEN and V. N. KARPENKO, An Axicell Design for the End Plugs of MFTF-B, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCID-19318 (1982).

3. G. A. CARLSON, W. L. BARR, B. M. BOGHOSIAN, R. S. DEVOTO, J. N. FOGGETT, G. W. HAMILTON, B. M. JOHNSTON, W. N. KUMAI, J. D. LEE, B. G. LOGAN, R. W. MOIR, W. S. NEEF, and R. B. CAMPBELL (TRW, Inc.), Comparative End-Plug Study for Tandem Mirror Reactors, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCID-19271 (1981).
4. S. A. MUELDER, A Monte Carlo Analysis of Neutron Effects Within the MFTF-B Vault, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-86079 (1981).
5. J. A. DAY and L. L. GEORGE, Opportunistic Replacement of Fusion Power System Parts, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85894 (1981).

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government thereof, and shall not be used for advertising or product endorsement purposes.

TABLE I. Performance Parameters for Axicell MFTF-B

Parameters	Value
Central-cell density, n_c	$4.8 \times 10^{13} \text{ cm}^{-3}$
Central-cell ion temperature, T_{ic}	15 keV
Central-cell electron temperature, T_{ec}	9 keV
Central-cell axial field, B_c	1-1.6 T
Effective central-cell length, L_c	13 m
Plasma radius/ion cyclotron radius, r_c/ρ_i	13
Confinement lifetime, τ	1 s
Density-lifetime parameter, $n\tau$	$5 \times 10^{13} \text{ cm}^{-3} \cdot \text{s}$
Axicell high-field peak, B_2	12 T
Axicell low-field peak, B_1	6 T
Yin-yang anchor central field, B_A	1 T
Yin-yang anchor mirror field, B_M	3 T
Plasma energy gain for D-T equivalent (depending on mode), Q	0.2-0.6
Central-cell plasma pressure, β_c	0.4-0.7

FIGURE CAPTIONS

Fig. 1. Artist's conception of the completed Axicell MFTF-B. The 58-m-long vacuum vessel has been cut away to display the east-end magnets.

Fig. 2. Configuration of the Axicell MFTF-B magnets and vessel (south elevation view). The right half is cut away to show the configuration of the interior components. The passing-particle barrier beam (P2B2) on the right side would reside on the part removed with the cutaway.

Fig. 3. Computer-generated drawing of the Axicell MFTF-B magnet array.

Fig. 4. Magnetic field strength B , plasma potential ϕ , and plasma density n profiles for the three operating modes of MFTF-B: MARS, TDF (Kelley), and TMX-U. The MARS mode is presently favored as optimum for a tandem-mirror fusion reactor. The Kelley mode is an alternate. The TMX-U mode is a transitional phase only.

Fig. 5. Supervisory control and diagnostics system of MFTF-B.

Fig. 6. Planned Availability scheme for MFTF-B.

Karpenko - Figure 2

Karpenko - Figure 3

Karpenko - Figure 4

Karpenko - Figure 5

Karpenko - Figure 6