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ABSTRACT

A large, new Mirror Fusion Test Facility is under construction at LLL. Begun in FY78 it will be completed at the end of FY78 at a cost of $94.2M. This facility gives the mirror program the flexibility to explore mirror confinement principles at a significant scale and advances the technology of large reactor-like devices. The role of MFTF in the LLL program is described here.

DRAMATIC ADVANCES have been made in the physics of the magnetic mirror confinement approach to fusion energy production. These advances occurred both in the improvement in confinement by discovery of a technique for stabilizing mirror plasmas, and in the conception of new magnetic mirror configurations which could lead to substantially improved reactor systems.

To explore these ideas and to advance the technology of mirror-based reactor systems, the Mirror Fusion Test Facility (MFTF) was proposed and approved by the Energy Research and Development Agency for construction at the Lawrence Livermore Laboratory (LLL). Authorization of $94.2M has been given for the project and the facility construction began in FY78, with completion scheduled for the end of FY81.

Here we review the basis for proceeding with this major step in the mirror program, the role of MFTF for further research, and implications for reactor-like devices to follow MFTF.

MIRROR FUSION IDEAS

Confinement of plasmas by magnetic mirrors is an old conceput, but recent innovations have extended that concept to overcome problems both in physics and in reactor economics. The simple mirror system has evolved as shown in Fig. 1 to address such difficulties. Since the simple mirrors suffered from magnetohydrodynamic (MHD) instabilities, minimum-B (B for magnetic field strength) configurations were successfully adopted. This magnetic configuration produces field and plasma surfaces which are everywhere concave inward and has a minimum field at the plasma center, increasing outward. The result is to eliminate macroscopic instabilities which feed on magnetic energy released if the plasma expands outward.

Such a magnetic configuration is employed in 2XIIB, shown in Fig. 2, the experimental device on which further important discoveries, leading to the MFTF proposal, were made. The characteristic double fan-shaped plasma, and the Yin-Yang magnet which produces it are located in the center of the machine. The plasma is provided by pulsed streaming guns and is maintained by 20 kV neutral beams (7 MW pulses of 10 ms duration). Prominant in the figure is the large vacuum and cryopanel region for plasma expansion and pumping which is characteristic of mirror devices.

The important discovery on 2XIIB was the ability to control the Drift Cyclotron Loss Cone (DCLC) instability which was responsible for the high loss rates in the machine. Control is exercised by injecting low-energy plasma to fill the "loss cone" in velocity space, thus producing a stable particle distribution function. The result is to increase the energy containment time to near-classical values and to allow the plasma density to increase to densities $\sim 10^{20}$ particles/m^3 while the beams are on.

Deleterious effects accompany the injection of the warm plasma needed for stabilization, namely the cooling of plasma electrons which, in turn, leads to more rapid ion energy loss by "electron-drag". Larger plasmas with weaker density gradients are less unstable to the DCLC, according to theory, hence require less warm plasma stream for stability. One objective of MFTF is to test this theoretical scaling prediction. If true, electron temperatures of 1 keV and a Lawson parameter of 10^{18}sec/m^3 should be attained.

Another important feature of mirror plasmas is a positive ambipolar potential created by the mirror contained ions. A key result is that ions are lost after fewer scattering events in the presence of this potential hill. Reactor energy balance calculations reflect this fact by showing a lower system Q (the inverse of the circulating power fraction) because of the ambipolar potential. In fact, the traditional single cell mirror reactor has always been a marginal system from an energy balance viewpoint, hence ways to improve Q have often centered on changing the ambipolar potential.

In the evolution of mirror systems, the tandem mirror of Fig. 1 emerged from considerations

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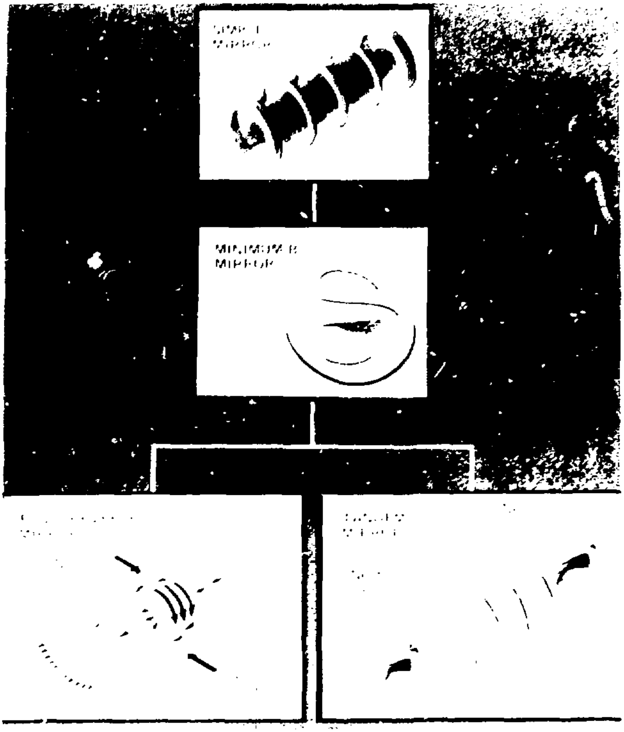
SIMPLE MIRROR
MINIMUM B MIRROR

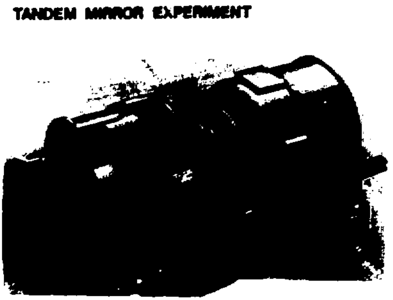

Fig. 3 - The Tandem Mirror Experiment (TMX) at LLL

DESCRIPTION OF MFTF

The MFTF facility is to be located in an existing LLL building (Bldg. 431) having a large concrete vault. The vault has 7-foot thick walls, and measures 67' x [illegible] x 74' high. Inside the vault a cylindrical fusion chamber housing the magnet is located as shown in Fig. 4. Other important items included in the facility are a site for the sustaining neutral beam power supplies (250 MW from the Pacific Gas and Electric grid to power 24 supplies with 80 kV dc output at 88A), a 7,000 sq. ft. remote control building, and a westward extension of Bldg. 431 for future uses of the facility (notably to allow for operating a tandem mirror device with apparatus constructed for MFTF). This site layout is shown in Fig. 5.

At the heart of the MFTF is the fusion chamber which houses the superconducting magnet, provides the high vacuum and physically supports the neutral beam source modules and target plasma guns. Diagnostic access ports through the chamber are also provided. An early design of the fusion chamber is shown in Fig. 6 and differs from the present design only in its vertical rather than horizontal orientation. The chamber is 12 m diameter and 18 m high and is filled with liquid helium-cooled cryopanels to pump the anticipated gas loads. A 3 kW helium refrigerator is required for the magnet and cryopanel cooling.

One of the more advanced technologies employed in MFTF is that of superconducting magnets. The MFTF magnet in Fig. 6 uses NbTi conductor at 7T, weighs 200 tons, and stores 500 MJ of energy. It provides a 2:1 mirror-ratio field, with mirror points 3 m apart. As such, it will be one of the largest superconducting magnets ever constructed. Further, the unusual Yin-Yang shape presents challenging design and fabrication problems.

Conductor for the magnet was developed by LLL and features a wraparound copper stabilizing sheath. The multifilamentary NbTi core is a 1/4" x 1/4" square with 420 embedded filaments. The wraparound conductor allows 50% of the core to be directly cooled through spiral channels, and gives an overall conductor dimension of 1/2"x1/2". The coil uses ~160,000 ft of this conductor.

Power supplies for the 80 kV neutral beam sources are a major part of the MFTF facility, accounting for ~50% of the total cost. Each of the 24 units has an accel power supply with 80 kV dc output at 88A, a gradient grid supply, arc and filament supplies, and a switching modulator to energize and protect the sources. The site for these supplies is ~2,000 ft. from the MFTF facility, on a pad with the substation. Since the recent success of the mirror machine can be attributed directly to the availability of neutral beam power for plasma buildup and sustenance, the importance of these beams to a mirror facility cannot be overstated.

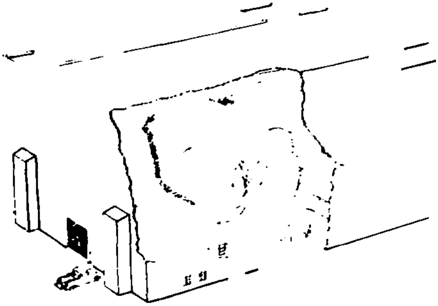

Fig. 4 - Building 431 at LLL containing the MFTF fusion chamber in a concrete vault

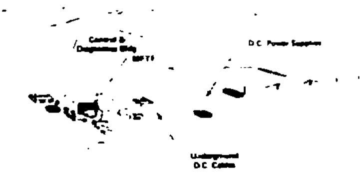

Fig. 5 - The MFTF site, including Bldg. 431, the remote control building, and the neutral beam power supply location

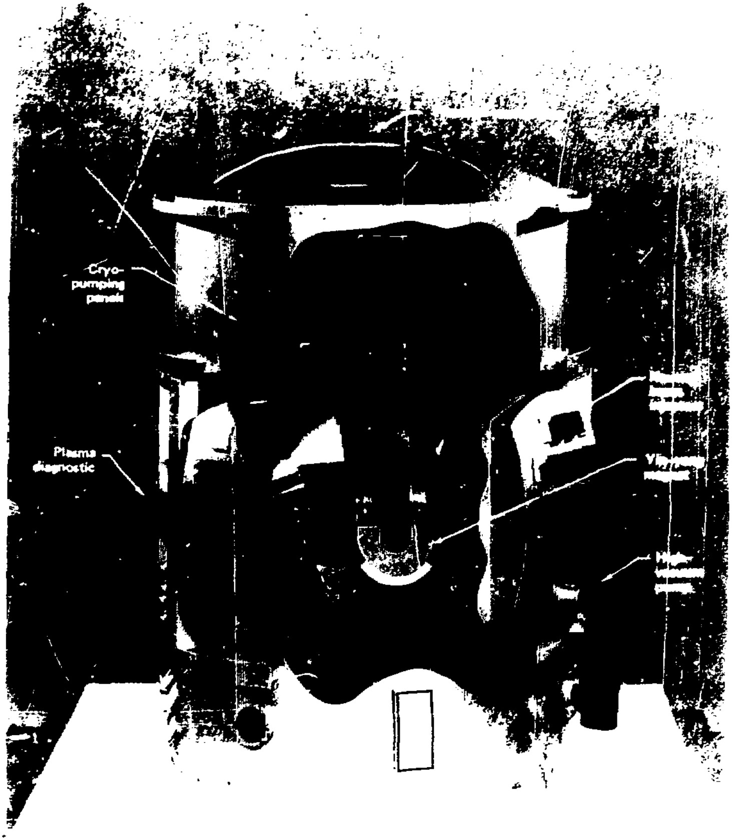

Fig. 6 - The fusion chamber (now oriented horizontally) housing the MFTF magnet, with extensive cryopanel cooling structures.

Another challenging technology is that of ion sources. Each of the 24 30 kV MFTF sources has ~6 1/2 MW input, of which ~2 MW eventually is absorbed in the plasma. Figure 7 shows the source, which consists of an arc chamber to produce a plasma and an 80 kV extractor system of 4 grids for accelerating the ions into a neutralizing chamber. From this chamber the neutrals pass through the magnetic fields in MFTF and are absorbed by the plasma created by streaming guns and startup neutral beams. The 24 startup beams provide 1000 A at 20 kV for 10 ms, while the sustaining beams provide 750 A at 80 kV.

To control the operation of the facility and provide for data acquisition and display, a sophisticated computerized control facility is planned. Supervisory control computers are provided at 3 levels of control, a system

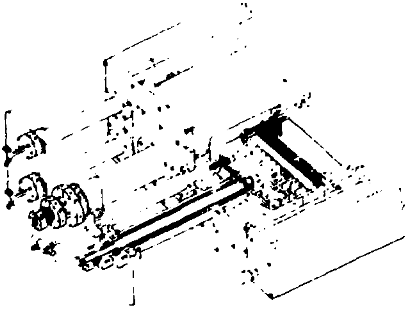

Fig. 7 - An 80 kV sustaining neutral beam source with 6½ MW power input

supervisor, a set of lower-level supervisors for the vessel, facility, and injectors, and an additional set of supervisors for the injectors (for streaming guns, startup beams, and sustaining beams). A data base manager and diagnostics data processors are also connected to the supervisory control systems as shown in Fig. 8. In addition, ~70 local control computers (LSI-11's) are used for component parts and sub-systems to collect and process information from these parts and to control and set parameters. Local controls and interfaces to diagnostic instruments also allow for processing and display of information of importance to experimental physicists.

ROLE OF MFTF

Successful completion and experimentation in MFTF will represent substantial progress in the Mirror program. Not only will the advances in technology represent significant steps toward reactor devices, but the achievement of the physics goals stated earlier mean that the demonstrated system "gain" of fusion power output relative to the input beam power is within one order of magnitude of that required for a "breakeven" demonstration. This point is illustrated in Fig. 9, which shows the projected operating regimes for the current set of fusion devices. The Lawson parameter and ion temperature are the coordinates with "gain" as a parameter, and the characteristic high plasma temperatures of mirror devices owing to their production by high energy beams is evident. Not shown is the equivalent gain of MFTF if operated with D-T rather than D-D. With D-T MFTF would have a power gain of 10^{-1}, comparable to TFTF, hence the order of magnitude gap to breakeven.

While these parameter demonstrations are important and correctly characterize progress, the benefits of MFTF lie in the opportunity to explore the new regimes of physics and technology associated with high temperature plasmas sustained for many seconds.

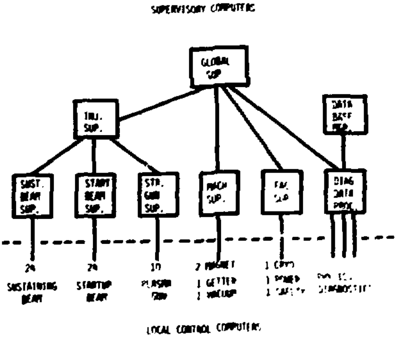

Fig. 8 - Functional block diagram of the MFTF computerized control system

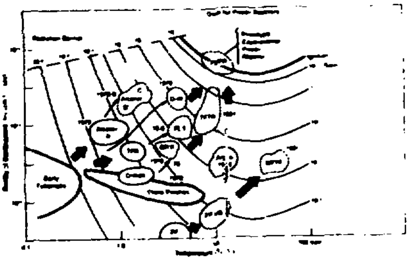

Fig. 9 - Operating parameters for past and present fusion experiments showing the progress toward a scientific demonstration