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C. C. Damm

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EVOLUTION OF THE MIRROR MACHINE

C. C. Damm

Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

ABSTRACT

The history of the magnetic-mirror approach to a fusion reactor is primarily the history of our understanding and control of several crucial physics issues, coupled with progress in the technology of heating and confining a reacting plasma. The basic requirement of an MHD-stable plasma equilibrium was achieved following the early introduction of "minimum-B" multipolar magnetic fields. In refined form, the same magnetic-well principle carries over to our present experiments and to reactor designs. The higher frequency microinstabilities, arising from the non-Maxwellian particle distributions inherent in mirror machines, have gradually come under control as theoretical prescriptions for distribution functions have been applied in the experiments. Even with stability, the classical plasma leakage through the mirrors posed a serious question for reactor viability until the principle of electrostatic axial stoppering was applied in the tandem mirror configuration. Experiments to test this principle successfully demonstrated the substantial improvement in confinement predicted. Concurrent with advances in mirror plasma physics, development of both high-power neutral beam injectors and high-speed vacuum pumping techniques has played a crucial role in ongoing experiments. Together with superconducting magnets, cryogenic pumping, and high-power radiofrequency heating, these technologies have evolved to a level that extrapolates readily to meet the requirements of a tandem mirror fusion reactor.

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I. INTRODUCTION

The concept of a magnetic-mirror machine as a fusion reactor was born more than 30 years ago in the earliest days of the Controlled Thermonuclear Research project at the University of California. Since that time, the concept has evolved through several stages as our understanding of the plasma physics has progressed and as improvements in relevant technologies have expanded engineering capability.

The four major stages of mirror machine development are depicted in Fig. 1. In the following text, these stages are described from a historical point of view--from the simple mirror of the first experiments to the mirror machine in its present form, the tandem mirror with thermal barriers.* The latter design addresses all of the plasma physics issues and reactor requirements that have guided the evolution and, at the same time, retains the engineering simplicity of a uniform, linear, power-producing central cell.

Reactors incorporating the thermal-barrier tandem mirror approach are highly competitive with other forms of fusion reactors and thus, motivate the strong programs in tandem mirror research presently underway in the United States, Japan, Germany, and the Soviet Union.

*For more detail than is possible to include in this paper, refer to the book Fusion, edited by E. Teller (Academic Press, 1981, Vol. 1, Part A).

II. BASIC PRINCIPLES AND EARLY EXPERIMENTS

In magnetic fusion devices, the basic isolation between the high-temperature fusion plasma and the material walls of the surrounding vacuum vessel occurs because the electrically charged fuel ions (and accompanying electrons) must gyrate along the magnetic flux lines, moving only slowly (for instance by collisional transport) across the field. Longitudinal motion is not so constrained, and particles may move freely (in helical orbits) along a uniform field. To achieve the long-time fuel confinement necessary for an efficient nuclear burn, this longitudinal flow must be controlled. Toroidal devices solve the problem by wrapping the field lines around to close on themselves. An alternative approach is to retain a linear configuration but cause the particles to reflect repeatedly toward the center of the device by introducing a stronger magnetic field at each end. These strong-field regions act as "magnetic mirrors," effectively inhibiting the longitudinal escape of the fuel ions.

Ions gyrating at the center of the device will be reflected by the mirror unless their velocity vector lies too nearly parallel to the flux line direction--within the so-called "loss-cone" angle. Eventually, Coulomb collisions will cause all ions to enter the loss-cone angle and escape. Higher-energy ions are confined longer since the characteristic Coulomb scattering time increases rapidly as the ion temperature (T_i) is increased ($\tau \propto T_i^{+3/2}$). As was soon recognized, this mechanism provides the classical upper limit to confinement by magnetic mirrors.

The mirroring effect of the earth's magnetic dipole was recognized by Störmer and others in the 1930s in connection with cosmic ray effects. An early demonstration of mirror action in a laboratory plasma was the objective

of a 1952 experiment of Post and Steller,⁽¹⁾ performed at the University of California Radiation Laboratory in Berkeley. In this experiment, a set of magnet coils produced a uniform central field in a glass tube, and could be operated with or without mirror fields at each end. A pulsed, electrodeless, radio frequency (rf) discharge was formed within the tube, and the attenuation of a microwave signal propagating through the tube was monitored. At the termination of the discharge, the attenuation diminished as the plasma density decayed. Comparison of this decay with and without mirrors clearly showed the effect of the mirrors in prolonging the plasma presence. Admittedly primitive, these experiments nevertheless provided encouragement to press on with development of better confined, higher temperature plasmas. Shortly thereafter, mirror research was established as part of the fusion program at the newly formed Radiation Laboratory in nearby Livermore, California.

An early set of experiments at Livermore attempted to reach higher plasma temperatures by compressional heating of a plasma trapped in a time-rising field. This heating, as well as the basic mirroring action, is based on the constancy of the magnetic moment $\mu \equiv W_{\perp}/B$ of a particle in a magnetic field, where $W_{\perp}$ is the energy associated with particle motion perpendicular to the field direction and B is the field intensity. Conservation of μ requires only that the spatial and temporal field variations are small compared with the particle gyroradius and gyroperiod, respectively. Effective heating requires that the field be increased slowly enough to meet this adiabaticity requirement, but rapidly enough to win over other loss processes.

Following the method described above, the Table-Top Experiments at Livermore in the 1950s heated electrons by this method. The small electron gyro-orbits remained adiabatic even with substantial final-to-initial field ratios. Starting with initial bias fields of 0.001 to 0.01 T and pulsing up

to 1 T in a few hundred microseconds, researchers achieved electron temperatures in the 20-keV range.⁽²⁾ These experiments demonstrated mirror confinement for many thousands of reflections, confirming the basic idea of a mirror machine. Moreover, the hot-electron plasma formed a useful analog of the hot-ion plasma for magnetohydrodynamic (MHD) stability studies, showing in particular the stabilizing effects of "line-tying" by conduction to metallic end walls.

The comparable ion-heating experiments in the "Toy-Top" apparatus at LLNL faced a tougher technological problem because the higher ion momentum at a given energy required stronger fields for adiabatic (μ -conserving) confinement. Fiberglass-reinforced pulsed coils were developed at Livermore, reaching fields of 14 T in the early magnets and up to 40 T in later small-bore (2.54 cm) coils. Plasma was formed by a spark between two deuterium-loaded wires and compressed in the rising field.

These experiments evolved into the multistage compression-transfer experiments (Toy-Top II and III) in which higher compression ratios were achieved by staged heating in successively smaller bore magnets. The plasma source became the deuterium-loaded, titanium "washer-stack" injector, which was capable of delivering up to 10^{16} particles/pulse at a mean energy of 300 to 800 eV. By 1960, after a two-stage compression, mean ion energies of 3 keV at densities of $2 \times 10^{13} \text{ cm}^{-3}$ were achieved.⁽³⁾

A third early experiment at Livermore, FELIX⁽⁴⁾, was designed to trap and heat pre-accelerated ions in a time-rising field, and thereby reach higher energy with smaller compression ratios. Although space-charge problems at the injector limited the densities that could be achieved, valuable experience in ultra-high vacuum techniques was acquired as the operating pressure was lowered to control charge-exchange losses of energetic ions. The device had

gold-gasketed seals and was bakeable to 400°C, yielding base pressures of about 10^{-9} Torr.

Meanwhile, a mirror program at Oak Ridge National Laboratory (ORNL) was underway. The DCX mirror experiment⁽⁵⁾ had been launched in an attempt to build a hot-ion plasma by injecting 600-keV molecular deuterium ions into a static magnetic field. Collisions with particles in an off-axis arc were used to break up the beam ions into atomic ions, thereby trapping them in circular orbits around the axis of the machine.

III. MHD STABILITY AND IOFFE BARS

The 1958 Geneva United Nations (UN) Conference on the Peaceful Uses of Atomic Energy instigated the declassification of research on fusion power by the United States, the United Kingdom (UK), and the Soviet Union. It was evident that at this time Soviet mirror research had advanced comparably to the U.S. program and included research on "magnetic traps"--their designation for mirror machines. A substantial injection experiment called OGRA (similar to DCX at ORNL) was underway at the Kurchatov Institute in Moscow. Soviet researcher Artsimovich reviewed the entire Russian program at Geneva.⁽⁶⁾

Following the 1958 UN conference, activity in mirror research increased. In general, attempts to increase plasma parameters followed two approaches--either pulsed compressional heating or change-of-charge-state injection of preheated fuel ions into static fields. In the former category were the MTSE⁽⁷⁾ experiments in the UK, DECA⁽⁸⁾ at Fontenay-aux-Roses in France, and the extension of the Toy-Top sequence at LLNL. The injection experiments split into molecular ion injection--OGRA, DCX-1, and DCX-2--and the new neutral-atom injection experiments--PHOENIX⁽⁹⁾ in the UK and ALICE⁽¹⁰⁾ at LLNL.

All experiments recognized control of background gas to be of prime importance, not only because of radiation losses from impurity ions but particularly because of particle loss by charge-exchange of fuel ions with gas. High-speed pumping was achieved by gettering on large areas of freshly deposited layers of titanium and other metals. Injection experiments were especially sensitive to charge-exchange losses because trapping rates were weak and density buildup was relatively slow.

By now, several experiments were encountering losses due to MHD instability. For instance, the plasma in Toy-Top was observed to cross the magnetic field, reaching the wall at the end of the second compression stage. The idea of MHD "flute" instability in a simple mirror field had been proposed earlier by Teller.⁽¹¹⁾ Except for special cases, such as where "line-tying" effects short out the perturbed electric fields by conduction to the end wall, serious plasma loss could be expected. At Geneva, Berkowitz et al.⁽¹²⁾ showed theoretically that cusp fields with reversed magnetic gradient would solve the problem.

A few years later, in one of the classic experiments in mirror plasma research, Ioffe and co-workers in the PR-6 experiment⁽¹³⁾ in Moscow demonstrated that a reversed-field gradient did indeed suppress the gross MHD instability. Ioffe added a set of six, longitudinal, current-carrying bars to a simple mirror field, providing a hexapole cusp field to reverse the gradient beyond a given radius. Plasma would then be confined in a region of minimum magnetic field ("minimum-B"), otherwise known as a "magnetic well." The plasma decay could then be followed with and without the hexapole windings energized. The effect was dramatic: the fluctuation level in the plasma was decreased by orders of magnitude as the bars were energized. Plasma losses were greatly reduced.

Control of MHD stability by this method was quickly tested in other experiments, both pulsed and injection, with uniform success. For example, a duodecapole "Ioffe-bar" field was applied to the ALICE neutral-injection experiment; the results are shown in Fig. 2.⁽¹⁴⁾ Low-frequency fluctuations virtually disappeared and the density, in the face of reduced losses, increased by a factor of 5. A similar result was obtained in later ALICE experiments with octupole windings, with an even larger gain in density.

The magnetic well principle demonstrated by Ioffe was put on a firm theoretical basis by Taylor and others,⁽¹⁵⁾ including a prediction that high-beta plasma could be confined (beta is the ratio of plasma to magnetic field pressure, high-beta being important in reactor economics). The multi-polar Ioffe-bar configuration soon evolved into the more efficient quadrupole "baseball" seam magnet--the second stage in Fig. 1 (first suggested by British physicists as a "tennis-ball" seam coil)--and later to the even more efficient yin-yang quadrupole of Moir and Post.⁽¹⁶⁾ Today, these yin-yang quadrupoles function as the end-plug magnets of the thermal-barrier tandem mirror shown in Fig. 1 where, in addition to magnetic efficiency, they provide better access for neutral beam injection.

To the present day, almost all mirror experiments rely on minimum-B magnetic wells for control of MHD stability, although there is a price. Technologically, the high-field magnets needed for reactors are more difficult (and thus costly) to build in quadrupole geometry. Furthermore, the lack of axial symmetry in the field introduces the possibility of increased radial losses. Nevertheless, the extreme effectiveness of this principle in dealing with the MHD problem overrides the difficulties, and our present tandem reactor projections include quadrupole MHD "anchors."

IV. THE MICROINSTABILITY ROADBLOCK

With the successful suppression of the low-frequency MHD fluctuations, gross loss of plasma on a machine-transit time scale was eliminated. But the gains in plasma parameters were limited; a new class of plasma instabilities was exposed as the chief impediment to the long confinement of high-temperature mirror plasma. These were the high-frequency (usually close to the ion gyrofrequency) wave-particle-type modes called microinstabilities. Stimulated by the non-Maxwellian particle distributions inherent in mirror confinement, these modes cause particle diffusion in velocity space, with eventual loss through the mirror "loss-cone." Although considerably slower than the gross MHD losses (hence largely masked prior to the magnetic well), the microinstability losses still may substantially exceed Coulomb rates and severely limit confinement. It was to take more than a decade of investigation, often discouraging, before a pathway to control of these modes was demonstrated.

One of the first of the microinstabilities to be observed was the negative mass mode, seen and identified most clearly in DCX-1.⁽¹⁷⁾ Already familiar in accelerators, this mode caused severe losses in the Oak Ridge experiment, restricting the achievable plasma density by a factor of 10. Because the mode depends on the variation of gyrofrequency with radius, it is cured in magnetic wells. In the ALICE experiment with octupole Ioffe bars, a resultant decrease of high-frequency signals when bars were energized was interpreted as elimination of the negative mass mode.

The other microinstabilities were not so easily eliminated. Depending on details of particle distributions in velocity space, a whole array of modes began to be identified: "Harris," "Dory, Guest, and Harris," "convective

loss-cone," "drift-cyclotron loss cone," "two-component," and others. The theory and understanding of these modes developed steadily as the experiments turned up each new effect.

In the very similar PHOENIX and BASEBALL I neutral-injection experiments, the plasma density buildup was especially sensitive to the losses from instability modes. Both experiments relied on Lorentz-force ionization of highly excited beam atoms to build the plasma density, starting from a well-controlled vacuum environment that greatly reduced losses by charge-exchange. The excited atoms constituted only a small fraction ($\sim 10^{-3}$) of the injected beam, which itself was only about 0.1 A equivalent at best. The resulting weak trapping rate was quickly balanced by microinstability losses, inhibiting buildup beyond densities in the 10^9 - 10^{10} cm^{-3} range.

The BASEBALL II experiment at Livermore attempted to correct the microinstability by broadening the ion distribution through Coulomb scattering at low density, before the onset of instability. Specifically, three changes were made:

- Atom energies were dropped from 20 keV to about 2 keV to favor collisional broadening;
- The vacuum was further improved by careful control of gas from the injector;
- The magnet was made superconducting to accommodate longer (30-s) injection cycles, corresponding to the lengthened charge-exchange times.

The technology was successful: a 4-T mirror field, a steady-state operation, a 5×10^{-12} Torr base pressure in the cryogenic pumping environment, and a steady-state neutral beam at 2 to 5 keV. But to no avail--buildup stalled at the same place.

Meanwhile, the Toy-Top compression experiments had evolved to become 2X (so named because it was twice the diameter of Toy-Top), with extensive titanium gettering for gas control and minimum-B windings for MHD stability. However, high levels of rf turbulence were encountered, and although some improvement could be realized by adjusting operating parameters, poor confinement persisted. Conversion to a yin-yang magnet set (2XII) did little to change the basic picture, and the instability responsible for the anomalous loss rate persisted.⁽¹⁸⁾

Other experiments around the world faced equivalent difficulties. Neither the compressional heating approach nor the plasma buildup approach by beam injection in a static magnetic field had shown the way to the high-temperature, high-density regime of the fusion reactor. Progress towards a mirror reactor at this point (circa 1972) was stymied.

V. TARGET PLASMA AND BREAKTHROUGH

There was one hope for achieving a high-temperature high-density plasma: use a target plasma to efficiently trap particles from a high-intensity neutral beam, relying on control of the particle distribution to limit the effects of microinstabilities.

A target type of buildup had been tried earlier at ORNL in the DCX experiment, but buildup was limited by heavy losses in the arc, as well as by instability. Another target buildup approach, also at ORNL, was tried in the INTEREM⁽¹⁹⁾ experiment. This target was formed by electron-cyclotron resonant heating (ECRH), but densities were also limited by low injection currents and charge-exchange.

Another target-generation experiment, LITE⁽²⁰⁾ at United Aircraft Research Laboratory in Connecticut, used a high-powered pulsed laser to irradiate a lithium-hydride pellet suspended electrostatically in a quadrupole field. Their favorable results encouraged a similar development on BASEBALL II. In this latter experiment, frozen, charged ammonia pellets were steered by real-time computer control to a laser focus spot at the center of the magnetic field. A high-powered pulsed CO₂ laser irradiated the pellet and generated a target plasma suitable for beam trapping.⁽²¹⁾ Just at this time, however, the buildup problem was solved in another, simpler way (see below), and interest in laser-pellet target generation diminished.

One of the keys to a successful buildup was the development, starting in 1970, of a truly high-current neutral beam at Lawrence Berkeley Laboratory (LBL). By 1973, a developmental module with a 10-A (equivalent) beam output at 20 keV was installed on 2XII at LLNL, using the compressionally heated plasma as a target. Although the current was known to be insufficient to sustain the density, the injection process worked and did not drive any new instabilities.

Plans were made to modify 2XII for a longer magnetic field duration (10 ms) and with a set of 12 high-current neutral beam injectors, each rated at 20 keV and 50 A. While development of the beam modules was in progress, the new magnet set was designed and built. By January 1975, experiments began in the configuration, now called 2XIIB, illustrated in Fig. 3. But with injection of beam currents up to 350-A equivalent, intense rf fluctuations were observed; it seemed that microinstabilities were once again in charge.

An earlier theoretical prediction by Post⁽²²⁾ that loss-cone instability modes could be suppressed by partial filling of the missing low-velocity end of the ion distribution prompted the 2XIIB experimenters to

provide an extended plasma burst from one of the plasma gun injectors. This low-energy plasma stream successfully suppressed the rf turbulence, and the density of confined energetic plasma increased. Furthermore, ion energy increased from 3 to 13 keV, the density reached $4 \times 10^{13} \text{ cm}^{-3}$, and the confinement parameter $n\tau$ was shown to increase with $E^{3/2}$, confirming the basic mirror theory, and reaching $0.7 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$. A substantial plasma beta of 0.4 was attained.

In addition, 2XIIB demonstrated that the same parameters could be reached using the stabilizing plasma stream as a target rather than the higher-energy target formed by magnetic compression. Thus, buildup could proceed in a static field with no need of compression, providing a simple solution to the long-standing startup problem. To extend the plasma duration beyond the limited plasma gun burst, a gas jet was introduced and ionized by the hot plasma. The resulting warm plasma enabled the contained plasma density to increase to $2 \times 10^{14} \text{ cm}^{-3}$, with beta values near unity. A typical buildup record is shown in Fig. 3.⁽²³⁾

The microinstability suppressed by the warm plasma stream in 2XIIB was identified as the "drift-cyclotron loss cone (DCLC)," mode, because it was driven by the radial gradient of plasma density coupled with a loss-cone ion distribution. Theorists at Livermore (Baldwin, Berk, Pearlstein, and others) developed a detailed study of warm-plasma stabilization, which provided a firm basis for extrapolation of the plasma parameters. Much of their work has been reviewed by Baldwin, who described the entire microinstability picture in 1977.⁽²⁴⁾

Nevertheless, the success of 2XIIB came after many of the mirror programs around the world had been dropped in favor of other approaches to fusion. At Livermore, however, researchers were encouraged to press on towards reactor parameters.

The disadvantage of the warm-plasma stream stabilization of 2XIIB came from the increased energy transfer to the flowing plasma. With larger diameter plasmas (measured in ion gyroradii), the amount of warm plasma necessary for stabilization was predicted by theory to decrease so that electron drag losses would be reduced.

A large feasibility experiment based on this projection was proposed and initiated at LLNL in 1976; the Mirror Fusion Test Facility (MFTF). Based on a large superconducting yin-yang magnet pair, the plasma would be formed as in 2XIIB and sustained by 80-keV neutral beam injectors for up to 30 s. The magnet and cryogenic technologies of MFTF were based on continuing development as well as the BASEBALL II experience; the neutral beams represented a manageable extrapolation from the 2XIIB injectors.

An alternate technique for warm-plasma stabilization was demonstrated about this time in the PR-7 experiment in Moscow.⁽²⁵⁾ By creating a shallow potential well at the center of a mirror plasma with electron-cyclotron resonant heated electrons, a warm component of plasma was trapped. (This technique more nearly resembles the current approach for control of microinstabilities in the thermal-barrier tandem mirror).

At this point, the physics and technology of the mirror machine were beginning to fall into place, and it became necessary to consider more seriously the mirror machine as a reactor.

VI. HIGH Q AND THE TANDEM MIRROR

Even with all anomalous losses suppressed, the particle confinement in a mirror machine is limited by the fundamental process of Coulomb scattering into the mirror loss cone. Increasing ion energy to reduce this scattering is ultimately limited by adiabaticity requirements in practically achievable fields. Detailed reactor studies⁽²⁶⁾ in the seventies explored a wide parameter regime and showed that a reactor Q of about unity (Q is the ratio of fusion power to injected power) is all that can be expected in a simple mirror configuration. In such a device, recirculating power would be very high, and the prospect of an economic design seemed remote.

Fortunately, a new concept emerged about this time that would enable the mirror machine to reach a higher level of performance. Fowler and Logan⁽²⁷⁾ at LLNL and independently Dimov⁽²⁸⁾ and coworkers in the Soviet Union proposed a configuration, the tandem mirror, that would result in:

- Longitudinal confinement improved by orders of magnitude over the single mirror cell,
- A projected reactor Q in an economically interesting range.

Their ideas were related to Kelley's⁽²⁹⁾ concept of a three-cell mirror machine proposed some years earlier, and relied on the generation of a positive ambipolar potential in a normal mirror cell.

Electrons scattering more rapidly than the magnetically confined ions in a mirror cell are lost preferentially until a positive electrostatic potential (ϕ) develops. When ϕ becomes of the order of several times the electron temperature (T_e), only the hotter electrons can leave, and the loss rates of ions and electrons balance, as they eventually must. The

tandem idea is to place such a positively-charged mirror cell at each end of a long uniform central cell (see Fig. 1), thus inhibiting ion losses from the central cell. While the end cells have no higher Q than a simple mirror cell, the overall Q becomes high because the plasma in the large central cell volume is exceptionally well confined. In a reactor version, the central cell is the main power-producing region and the end cells form the electrostatic "plugs" for the reacting central plasma. Additionally, the quadrupole end cells provide MHD "anchoring" of the entire machine, and the end-loss plasma from the central cell improves microstability in the plugs.

Experimental tests of the tandem principle were made in the GAMMA-6 experiment⁽³⁰⁾ at Tsukuba University in Japan, in the Phaedrus experiment⁽³¹⁾ at the University of Wisconsin, and in the Tandem Mirror Experiments (TMX) at LLNL. The TMX results⁽³²⁾ are depicted in Fig. 4, along with the experimental configuration. Additional transition magnets are required to couple the axisymmetric central cell to the quadrupole anchors. The water-cooled copper coils provided a flat magnetic field pulse length of about one second, long enough for the 20-ms plasma-injection cycle. The confining potential peaks in each TMX end cell were generated by increasing the plasma density in these cells relative to the central region, the higher potential simply resulting from the requirements of quasi-neutrality at constant T_e .

Confinement in tandem geometry was compared with that in single-cell mirrors by Simonen.⁽³³⁾ As seen in Fig. 5, the improvement of orders of magnitude in $n\tau$ was realized in TMX, and was in close agreement with the loss rates described by the theoretical work of Pastukhov.⁽³⁴⁾

As for microinstability, the loss-cone modes were indeed suppressed by the central-cell leakage. Residual ion-cyclotron noise was identified as the "Alfvén ion-cyclotron" mode arising from the ion anisotropy in the end cells, due to the perpendicular beam injection. In the upgraded version of TMX, this mode was eliminated by the simple expedient of angled beam injection.⁽³⁵⁾

One final refinement was necessary to bring the mirror concept to its present state. Generating the plugging potentials at reactor parameters by increasing the end-cell density is very costly and would require an extreme technological effort. The high densities that are needed force ion energies high (to achieve a reasonable $n\tau$); in turn, the resulting high plasma pressure forces the magnetic field up so that beta does not exceed its limiting value. Two requirements--neutral beams at MeV energy plus yin-yang fields at 12 T or more--appeared; the tandem reactor seemed very difficult to realize.

However, the "thermal barrier" idea by Baldwin and Logan,⁽³⁶⁾ introduced in 1979, demonstrated how to get around these extreme requirements. By creating a dip in plasma potential at the appropriate axial location inboard of each end cell, the electron population in the central cell can be thermally isolated from the plug electrons. This allows the small plug volume of electrons to be economically heated to temperatures well above the central temperature and the potential correspondingly increased. Thus, the required confining potential can be generated with the plug density lower than the central density with a substantial savings of power to sustain the plug plasma. Again, MHD stability is maintained by the quadrupole anchors, and microstability is assured by penetration of the central-cell plasma to the confining potential peaks, now located at the

extreme ends of the machine just inside the outer yin-yang mirror. These ideas are currently under test in the Tandem Mirror Experiment-Upgrade (TMX-U) device at LLNL.

VII. CURRENT WORK

Other tandem experiments are now in preparation or in initial operation around the world: in Japan, the GAMMA-10 experiment; in Novosibirsk, the AMBAL experiment, and at the Massachusetts Institute of Technology, the TARA experiment. At LLNL, the MFTF machine has been converted to a large tandem facility with thermal barriers (MFTF-B) and will be ready for operation late in 1986. The superconducting magnet configuration for MFTF-B is shown in Fig. 1. A high-field axisymmetric cell has been added at each end of the central cell to reduce penetration of central plasma to the thermal barrier region. Power required to maintain the thermal barrier potential plug is thus reduced as well as radial losses in the quadrupolar fields. The plasma parameters for the MFTF-B experiment will yield verification of the physics scaling; the objective is to provide a scientific feasibility demonstration for tandem mirror reactors. Projected axial confinement parameters for the current tandem mirror experiments are shown in Fig. 5.

Meanwhile, at Karlsruhe in the Federal Republic of Germany, a tandem mirror design study of a near-term fusion engineering test facility, called TASKA, is underway. At LLNL, the Technology Demonstration Facility study aims at design of a similar device.

Our present concept for a tandem reactor is directly related to the MFTF-B configuration and is embodied in the Mirror Advanced Reactor Study (MARS)⁽³⁷⁾ almost completed. In this latter design, the MARS device features steady-state operation at high Q with a linear, power-producing central cell. From upcoming experimental results and further reactor studies, we expect the mirror approach to a fusion reactor to continue its evolution toward a commercial electrical power-producing application.

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FIGURE CAPTIONS

FIG. 1. Evolution of the mirror fusion confinement concept. The configuration shown as the tandem mirror with thermal barriers is the magnet set for MFTF-B, now under construction.

FIG. 2. The envelope of low-frequency oscillations in the ALICE experiment showing (a) a decrease when Ioffe bars are energized at t_1 . The fast-atom detector signal (b), which is proportional to density, increases by a factor of 5 until the injected beam is turned off. Weak oscillations reappear at t_2 when Ioffe bar current is turned off.

FIG. 3. Experimental configuration of 2XIIB. Buildup of hot-plasma density with neutral beam injection proceeds in the presence of a warm-stabilizing stream plasma. Gas injection acts to prolong the buildup by providing additional warm plasma. Dots show the buildup calculation is in agreement with the experiment.

FIG. 4. Experimental configuration of TMX. Plots of axial variation of magnetic field intensity B_c , density n_c , and potential ϕ_c show generation of the confining electrostatic potential peaks in the end-cell plasma. Points are experimental results.

FIG. 5. Variation of confinement parameter $n\tau$ with ion energy (or temperature). Points from many experiments verify single mirror theory; however, the TMX experimental point shows the improvement expected in tandem geometry. Projected values are shown as open circles.

C. C. Damm - FIG. 1

Simple mirror

Minimum-B mirror

Tandem mirror

Thermal barrier tandem mirror

C. C. Damm - FIG. 2

C. C. Damm - FIG. 3

C. C. Damm - FIG. 5

Technical Information Department • Lawrence Livermore Laboratory
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