

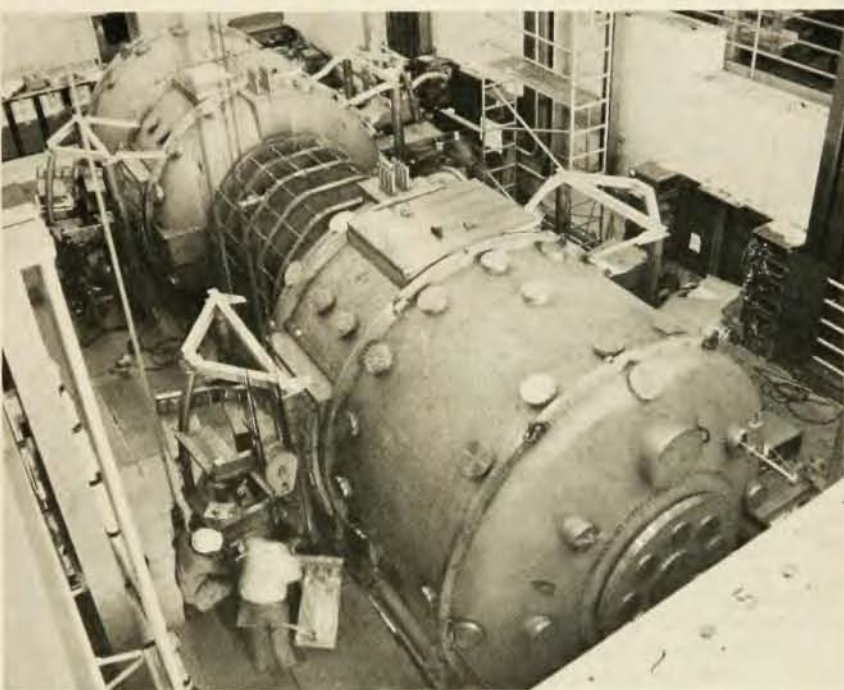
Tandem-mirror success leads to expanded MFTF

Two ideas advanced in recent years for improving the confinement of plasmas in mirror machines have added much to the promise of such devices as potential fusion-power reactors. In an experiment just completed at Livermore, the tandem-mirror configuration, first suggested in 1976, appears to have passed its first major experimental test with colors flying.¹ The more recently proposed thermal-barrier idea, which is expected to strengthen the confinement capabilities of the tandem configuration, will undergo its first experimental trial next year at this same Tandem Mirror Experimental Facility (TMX).

Given the promise and first successes of the new schemes, DOE has decided that the tandem configuration and thermal barriers ought to be incorporated into the large Mirror Fusion Test Facility now under construction at Livermore (PHYSICS TODAY, March 1979, page 17). This expansion of the MFTF project was strongly recommended in the recent report of the Fusion Review Panel headed by Solomon Buchsbaum (PHYSICS TODAY, August, page 21). If Congress approves, the expanded facility—named MFTF-B—will consist of two mirror machines “plugging” the ends of a central solenoid. The anticipated cost, \$226 million, is a bit more than twice that envisioned for the original single-mirror MFTF project, which had been authorized before the tandem scheme was introduced.

Mirror machines suffer more severely from the loss of plasma ions through Coulomb scattering than do tokamaks and other such closed-confinement machines. In open-confinement devices such as mirrors, where the magnetic field lines do not close on themselves within the plasma volume, an ion is easily scattered into a critical angular region surrounding an exciting field line. Having entered this “loss cone,” the ion quickly leaves the plasma along the field lines instead of being reflected back by their convergence.

The resulting higher rate of Coulomb-scattering loss would make it necessary for a mirror reactor to run at much higher plasma temperatures



Tandem Mirror Experiment at Lawrence Livermore Laboratory has just completed the first major test of the tandem configuration's ability to confine fusion plasmas. Two mirror machines plug the ends of a central solenoid 5.5 meters long by generating electrostatic barriers.

than a tokamak—hundreds rather than tens of keV. Because the Coulomb scattering cross section decreases with increasing energy, these higher temperatures more closely approximate a “collisionless” plasma. But even at an ion temperature of several hundred keV, says Fred Coensgen, leader of the TMX group, a single-mirror device could not achieve energy-confinement times long enough for it to serve as a practical fusion reactor.

Looking for ways to increase the confinement times of open magnetic-confinement systems, the Russians and the Americans in 1976 came up almost simultaneously with the idea of the tandem-mirror configuration. Kenneth Fowler and Grant Logan at Livermore, and independently, G. I. Dimov at Novosibirsk suggested that one use two mirror machines to plug the ends of a central solenoid (PHYSICS TODAY, February 1978, page 18).

This tandem configuration was intended to turn a well-known difficulty of mirror devices to advantage. Because the electrons leak out of the mirror even faster than do the ions, the plasma is raised to a positive electrostatic potential, which then exacerbates the rate of ion leakage. But, the inventors reasoned, if one places such a mirror machine at each end of a plasma-filled solenoid, the positive potentials of the end plasmas will effectively confine the central plasma in an electrostatic potential well.

The ability of the tandem configuration to generate such a potential well was demonstrated² in a small-scale device last year by S. Miyoshi's group at the University of Tsukuba in Japan. They achieved a well depth of 50 volts in a 3-meter solenoid between two mirror end plugs. But because the device had no heating capacity to maintain the temperature of the injected (pre-

heated) plasma, it was not possible to determine the improved confinement capacity directly, by measuring the confinement parameter (plasma density $\times$ confinement time).

Tandem Mirror Experiment. To measure the confinement parameter one needs a machine that heats the confined plasma for times long enough to establish thermal equilibrium. To this end Coengsen and his colleagues undertook the construction of the TMX in 1977. In the Livermore machine, the plasmas in the two end-plug mirrors are heated and sustained by 24 neutral beams with a mean energy of 13 keV per atom. The quadrupole confining field in each end mirror is produced by a coil shaped roughly like the seam of a baseball. This produces an end-plug plasma in the shape of a bow tie twisted by 90°.

Experiments at the TMX facility began in July of last year. The central 5.5-meter solenoid of the TMX is heated only by electrons that pass freely between the end plugs and the solenoid plasma. The Livermore group was gratified to find that this indirect heating was sufficient to maintain the temperature in the solenoid at 0.2 keV, compared with 13 keV in the end-mirror plasmas. In a tandem-mirror reactor the central solenoid plasma would also be much cooler than the end-plug plasmas—roughly 30 keV and 300 keV respectively. This points up one of the major virtues of the tandem configuration. All the high technology is confined to the end mirrors, which remain at moderate size no matter how big the reactor. One increases the power output of the reactor simply by increasing the length of the central solenoid—whose technological requirements are modest—while keeping the end-mirror sizes fixed.

The now completed first phase of the TMX experiment—without thermal barriers—has achieved a value of $n\tau = 1 \times 10^{11}$ sec/cm³ for the confinement parameter. This is a ninefold improvement over the best value attainable by single-mirror devices of comparable temperature, Coengsen told us. The electrostatic potential well in the solenoid was more than a hundred volts deep. The neutral beams delivered up to 2.5 million watts of heating power to each end mirror during pulses lasting 25 milliseconds.

The ratio of kinetic plasma pressure to the pressure of the confining magnetic field, β , is a measure of the efficiency with which the field confines the plasma. The greater the plasma pressure, the more fusion power one can achieve; the greater the field pressure, the more expensive the reactor. A significant advantage of open-confinement devices over toroidal machines is their ability to attain much higher

values of β . The necessity of maintaining the circulating plasma current that gives the tokamak field its characteristic helical twist limits tokamaks to β below 10%. Tandem-mirror reactors, Coengsen told us, should achieve much higher values of β —perhaps as high as 50%. The TMX has thus far achieved an average β of 20% in the solenoid, with maximum values near 50%. In general, he points out, the TMX has attained the performance parameters predicted for it.

Richard S. Post and his colleagues at the University of Wisconsin (Madison) are investigating an alternative to neutral-beam heating for tandem mirror machines. In a tandem device intermediate in size between the Tsukuba machine and the TMX, they are heating the end-plug plasmas with radiofrequency power at the ion cyclotron frequency. The group has thus far achieved a tenfold increase in the temperature of plasma injected into the end plugs. They have not yet reported the confinement of a central plasma in a tandem configuration.

A tandem machine similar in size and design to the TMX is currently under construction in Novosibirsk. The Soviets expect to have this AMBAL device ready for experiments by next June.

The thermal barrier idea, put forward³ by David Baldwin (Livermore) and Logan last year, remains to be tested. The intention is to improve the confinement of the central plasma by deepening the electrostatic potential well in the solenoid still further. This is to be accomplished by getting the electrons in the end plugs very hot without the necessity of excessively energetic neutral-beam heating. This will require some degree of thermal isolation, by curbing the free passage of the plasma electrons between the end plugs and the central solenoids.

To this end, local potential minima are to be generated at the interfaces between the end mirrors and the central plasma by locally reducing the plasma density at these junctions. This density reduction is to be accomplished by "neutral beam pumping." Carefully directed neutral beams are injected into these bottleneck regions to destroy the plasma locally by charge-exchange collisions. The beams convert plasma ions to neutral atoms, thus permitting their escape from the confining magnetic field. The injected particles are now charged, but they escape confinement because they were injected along the field lines.

These low-density potential minima should permit the attainment of very high electron temperatures in the end mirrors with modest rf heating at the electron cyclotron frequency. The hotter the electrons, the greater the elec-

trostatic barrier that confines the central plasma. This month the Livermore group will begin extensive upgrading of the TMX device to incorporate the thermal-barrier scheme.

MFTF-B. The decision to expand the MFTF project into a tandem device comes at a convenient time in the construction of this large mirror machine. At this stage none of the work already completed at Livermore on the original MFTF mirror needs to be redone. One can proceed directly with the construction of the second mirror and the 30-meter central solenoid. The tandem MFTF-B could run with or without thermal barriers, depending on the outcome of the forthcoming TMX trials. But, Coengsen assured us, "we expect the thermal-barrier test to succeed." With prompt Congressional approval, the facility would be scheduled for completion in about 1985.

The MFTF-B is intended to produce plasma conditions sufficient for "scientific breakeven"—fusion power out equal to heating power input. Note, however, that this facility will not actually use a deuterium-tritium fusionable fuel. Employing only hydrogen and deuterium, it is intended to simulate breakeven plasma conditions. With a central plasma volume 70 times that of the TMX, the MFTF-B should reach an ion temperature of 15 keV (2×10^8 K) and a confinement parameter of 5×10^{13} sec/cm³ in the solenoid. These values are comparable to what is expected of the large tokamaks currently under construction at Princeton and in England, Japan and Russia.

In place of the "baseball" coils employed in the TMX, the quadrupole mirror fields in the MFTF end plugs will be produced by pairs of "Yin-yang" coils, shaped roughly like the outline of a pair of cupped hands. Recent theoretical work, however, suggests that axisymmetric fields might do better than quadrupole fields. The MFTF-B design will be sufficiently flexible to permit a later conversion to axisymmetric end mirrors.

The fact that open-confinement reactors require higher plasma temperatures than do tokamaks may ultimately be turned to advantage. These higher temperatures would permit "advanced fuel cycles" such as D-D fusion, in place of the lower-temperature D-T cycle. Whereas in the D-T cycle 14-MeV neutrons carry most of the fusion energy output, charged particles (protons and helium nuclei) carry off most of the energy of the D-D cycle. This would permit the direct conversion of the fusion output to electrical power, largely bypassing the inherently inefficient thermal blanket required with neutrons. Furthermore, the D-D cycle would eliminate the need for tritium breeding, and would lessen the radioac-

tivity problems resulting from neutron activation of the reactor materials. But Fowler cautions that D-D reactors would require much better plasma confinement than would machines employing the D-T cycle.

—BMS

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CESR shows bare-bottomed mesons

In its first year of operation, the Cornell electron-positron storage ring, CESR, has provided strong evidence for the existence of a fifth quark flavor. The three narrow upsilons mesonic states near 10 GeV, first seen at Fermilab in 1977 and 1978, had offered the initial experimental evidence for a hadronic building block heavier than the charmed quark (see *PHYSICS TODAY*, October 1977, page 17 and January 1979, page 17). The Υ , Υ' and Υ'' were generally believed to be bound states of a massive new "bottom" quark, b , and its antiparticle.

But being $b\bar{b}$ bound states, these upsilons mesons would exhibit no *net* bottom flavor—just as positronium, the bound state of e^+e^- , has no net charge. It was felt that the case for the new flavor would not be made until one had actually seen "bare bottom" states—particles containing an unpaired b or $\bar{b}$ quark. (The reader who

objects to this vivid nomenclature may consider the only alternative usage in general circulation—"naked beauty.")

It seems that the production of bottom-flavored (B) mesons has now been observed. In April, two groups at CESR reported^{1,2} the observation of a fourth upsilons state (Υ'''), which appeared to be above the threshold for decaying into B and $\bar{B}$ mesons. In July, at the International High-Energy Physics Conference in Madison, both groups presented the first direct evidence for the production of these bottom-flavored mesons. The properties of the Υ''' and B thus far measured appear to be in good agreement with the expectations of the "standard model," which anticipates that a still heavier "top" quark will eventually make itself known.

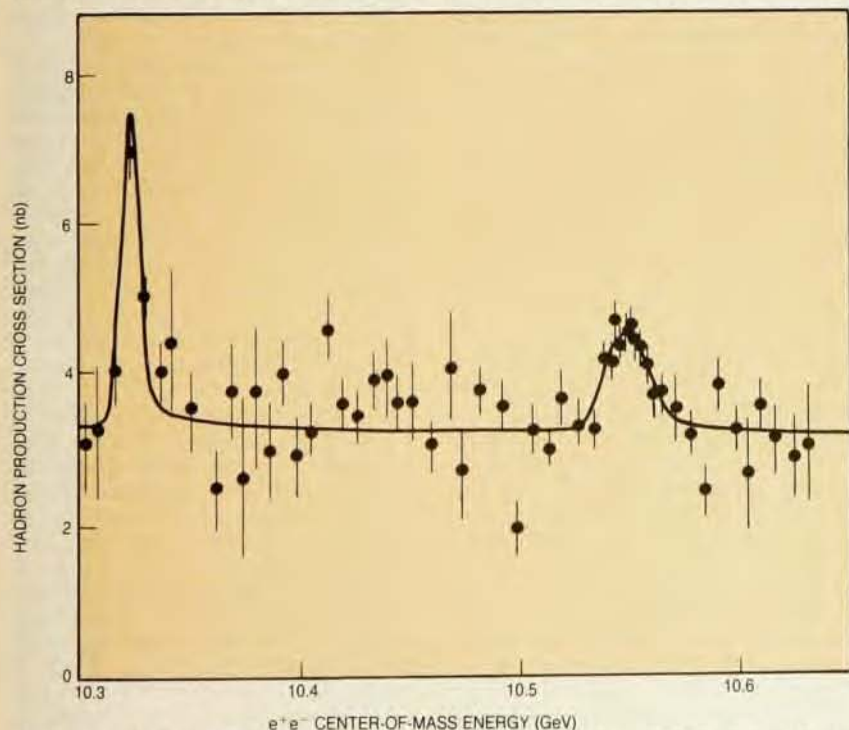
Resonant widths. The three lower-lying upsilons states, with masses near 9.4, 10.0 and 10.3 GeV, had been seen

first as resonant enhancements in the mass spectrum of $\mu^+\mu^-$ pairs produced in hadronic collisions at Fermilab. But these states are more easily studied in e^+e^- colliding-beam storage rings. The Υ'' was not well established until its existence was confirmed at CESR last fall. Experiments at CESR and the lower-energy storage ring, DORIS, at DESY in Hamburg, have found no detectable resonant widths for these three upsilons states, beyond the irreducible energy spread of the colliding beams. This puts an upper limit of about 1 MeV on the intrinsic widths of these resonances, making them at least two orders of magnitude narrower than what one would expect for conventional hadronic states. In fact, a study of the $\mu^+\mu^-$ decay mode of the Υ at DORIS puts its full width at only 60 keV.

The Heisenberg uncertainty principle tells us that the resonant width is inversely proportional to the lifetime of a state. When a state is unusually narrow, something is inhibiting its decay. For the three narrow upsilons states, just as in the case of the narrow J/ψ "charmonium" states (see *PHYSICS TODAY*, January 1975, page 17), that inhibiting mechanism is believed to be the absence of any energetically available decay channels that can be reached without quarks having to change flavor. If these upsilons were heavier than twice the mass of the lightest bottom-flavored meson in Nature, they could decay strongly into $B\bar{B}$ pairs. Flavor-changing processes can occur only in the weak interactions. Therefore, if the lightest B meson is too heavy, the only hadronic mechanism by which any of these upsilons can decay is the mutual annihilation of its b and $\bar{b}$ quarks. But this sort of self-annihilation is empirically known to be strongly suppressed.

Hence the excitement when the fourth upsilons state was found last spring, with an intrinsic width of about 20 MeV. This Υ''' , very broad by the standards of its three predecessors, was discovered at about 10.55 GeV in both of the major detector systems at CESR—the large magnetic detector, CLEO, of the Cornell, Harvard, Rochester, Rutgers, Syracuse, Vanderbilt collaboration and the nonmagnetic, sodium iodide CUSB detector of the Columbia, Stony Brook, Louisiana State, Munich collaboration. The sudden increase in width from one excited $b\bar{b}$ state to the next strongly suggested that the threshold for decay to $B\bar{B}$ lay somewhere between the Υ'' and Υ''' masses—implying a mass between 5.18 and 5.28 GeV for the lightest bottom-flavored meson.

A lowest B mass in this region agrees well with what one deduces from phenomenological models of quark-quark



Upsilon states Υ'' and Υ''' are seen as resonant bumps near 10.3 and 10.55 in the total cross section for hadron production in e^+e^- collisions. Data are from CLEO detector at Cornell CESR storage ring. Similar results were obtained by CUSB detector group, also at CESR. The fact that the Υ''' resonance is significantly wider than the three lighter upsilons states suggests that it lies above threshold for decay into bottom-flavored mesons.