new dosimetries appear to have closed the gap between the two data sets. Risk coefficients (death rates per rad) calculated by Dobson and Straume for gamma-induced leukemia and breast cancer are consistent at low doses with those promulgated in 1977 by the International Commission on Radiological Protection. At high gamma doses, however, the leukemia risk coefficients calculated at Livermore are four times as large as the dose-independent ICRP risk factor. For total cancer mortality, on the other hand, the new gamma radiation risk coefficients are lower than the ICRP value.

It is generally agreed that more work needs to be done before the new atomic-bomb dosimetries can provide a firm basis for a revised set of radiation-risk standards. Uncertainties remain with respect to the total yield of the Hiroshima bomb and the gamma doses coming from fission products in the fireballs. New estimates of structural and body shielding are yet to be calculated for the revised radiation spectra.

Dissenting from this cautious consensus, Radford argues that too much emphasis has been put on the leukemia and other mortality data, leading to underestimated gamma risks. The "more reliable" data on total cancer incidence (as distinguished from mortality), he contends, remove all differences between the two cities (without reference to neutron RBEs) and lend strong support to his belief that the dose–response functions are indeed linear. —BMS

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Reversed-field pinch stable 8 msec

Tokamaks are certainly in the vanguard of the quest for plasma ignition in magnetic-confinement fusion experiments. Nevertheless, the persistent concern that technological difficulties may ultimately render tokamaks of present-day design impractical as power reactors has encouraged a broad search for alternative magnetic-confinement concepts. One such alternative, the reversed field pinch (RFP), is an axisymmetric toroidal scheme very much like the tokamak. But the differences between the two could eventually prove to be of considerable practical significance.

A few months ago, the ZT-40 reversed-field pinch machine at Los Alamos experienced a dramatic hundredfold increase of its period of plasma stability immediately after its ceramic vacuum liner was replaced by a metallic liner. With this change, suggested by the earlier successes of the smaller "Eta–Beta II" machine in Padua (Italy), the ZT-40 has now achieved quiescent stability periods of 8 milliseconds—a world's record for RFPs. During these quiescent periods, the magnetic field at the edge of the plasma appears to maintain itself in the characteristic "reversed" configuration upon which stability depends in such devices.

With the successes achieved at Los Alamos, and similarly encouraging results coming from RFP experiments at Padua, Culham (England) and Tokyo, plans are afoot for the next generation RFP experiment. In July, the DOE Office of Fusion Energy convened a technical review panel to consider the proposal that the US become a full participant in the British RFX experiment. The RFX, currently being designed at Culham in collaboration with the Los Alamos and Padua groups, will be a reversed-field-pinch torus with three times the linear dimensions and plasma-current capacity of the ZT-40. The DOE would not at present consider an RFP of such size—estimated to cost about $40 million—as a purely American undertaking. Among the alternatives to tokamaks and mirrors considered by the DOE Alternate Concept Review Committee two years ago, only the Elmo Bumpy Torus was recommended for funding at the level of a proof-of-principle experiment (PHYSICS TODAY, October 1979, page 18). The RFP was however the Committee's clear second choice among nine alternative concepts.

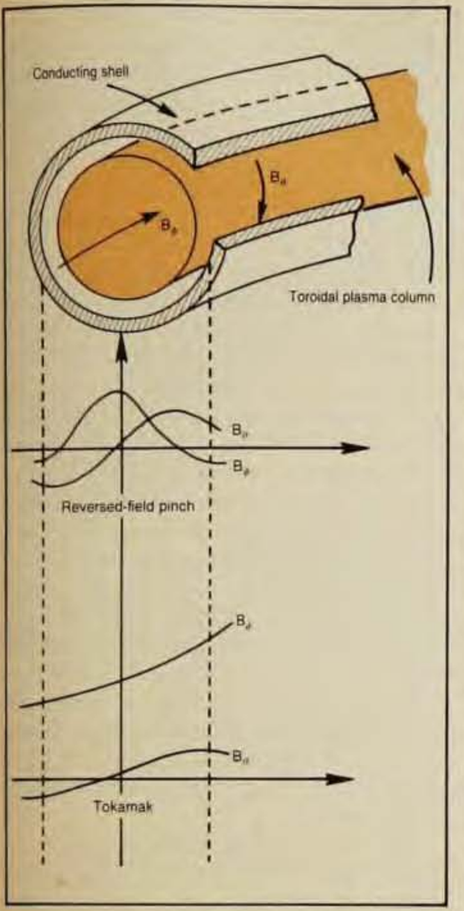
The principal differences between the tokamak and the RFP are the magnitude and profile of the toroidal component of the magnetic field and the magnitude of the plasma current. The toroidal field component B_ϕ, running the long way around the torus, is primarily generated in either machine by the current in the field coils wrapped poloidally (the short way) around the torus. The poloidal field component B_θ in both schemes is not generated directly by external coils, but rather by a toroidal current introduced in the plasma itself by transformer action. Because the plasma current in the RFP is much stronger than in a comparable tokamak, it also contributes significantly to the toroidal field, producing a strong variation of B_ϕ with distance from the center of the plasma.

The tokamak achieves plasma stability by having B_ϕ so large relative to B_θ that magnetohydrodynamic kink instabilities cannot fit into the torus. The larger the poloidal field component becomes relative to the toroidal component, the more helically twisted are the magnetic field lines as they travel around the torus. The requirement of tokamak stability imposes a strict limit on the degree of helical twisting; the field lines must traverse the torus at least once the long way before they complete a twist the short way. This is expressed by the Kruskal–Shafranov constraint: $q>1$, where $q=(B_\phi/B_\theta)/A$, and A is the "aspect ratio," the major radius of the torus divided by its minor radius.

Thus, for a given toroidal field strength the Kruskal–Shafranov constraint severely limits the magnitude of the plasma current that generates the poloidal field. This is perhaps unfortunate, because the ohmic heating generated by the plasma current would be the simplest way of heating the plasma to ignition temperature. The higher the plasma current, however, the greater is the toroidal field required to satisfy the Kruskal-Shafronov limit. But the larger the toroidal field, the greater is the cost of the machine and the magnetic stress on the coils.

The RFP simply ignores the Kruskal–Shafranov limit and the problems it presents. Not only does it operate stably with q less than one, q actually goes *negative* at the plasma edge. That is what's meant by field reversal: B_ϕ goes through zero and changes direction as one goes out from the center to the edges of the plasma. This field reversal is one of the two tricks that lets the RFP get away with violating the Kruskal–Shafranov limit. It turns out that the field-reversed configuration is a minimum-energy state of the plasma-field system, stable against localized MHD instabilities. The other trick is the presence of a thick conducting shell placed just outside the vacuum liner. Image currents generated in this shell stabilize the plasma against larger-scale MHD modes. A tokamak, operating at $q>1$, does not require such a conducting shell.

Circumventing the Kruskal–Shafranov limit, the RFP operates with a very modest toroidal field and very high plasma current. The strong poloidal field generated by the plasma current plus the plasma-generated variations in the toroidal field result in a field configuration of very high "shear." That is to say, the pitch of the helical field lines increases very rapidly as one goes from the center to the surface of the plasma. It is this high shear, culminating in the actual reversal of the pitch (hence the reversal of



Magnetic field profiles across RFP and tokamak plasmas. The tokamak toroidal field (B_ϕ) is large throughout the plasma and at the external coils. In the RFP, B_ϕ reverses its direction at the plasma edge and is very weak at the coils. The poloidal field (B_θ), generated by plasma current, is comparable to B_ϕ in the RFP.

B_ϕ) near the edge, that stabilizes the plasma against localized MHD modes.

The tokamak stability requirement, $q>1$, is replaced in the RFP by the less stringent condition that dq/dr, the derivative of q with respect to the minor radius, should not vanish anywhere inside the plasma. This accounts for the advantages that a successful RFP reactor would have over a tokamak:

▶ With no stability constraint on the intensity of the plasma current, an RFP could be raised to ignition temperature by ohmic heating alone. In a conventional tokamak, ohmic heating can supply only a small fraction of the necessary energy; neutral-beam heating or other complex auxiliary heating schemes are required. It has however recently been argued that compact, high-field tokamaks could get by without auxiliary heating (PHYSICS TODAY, May 1981, page 17).

▶ To stay within the Kruskal–Shafranov limit, the tokamak requires a small aspect ratio. Such a fat doughnut, with so small a hole at the center, presents all sorts of engineering problems for a tokamak reactor. The aspect ratio of an RFP reactor could be chosen on the basis of engineering convenience alone, with a central hole as capacious as one wishes.

▶ Large aspect ratio and low q also serve to reduce adverse "neoclassical transport" resulting from particles trapped by unintended mirror effects in the nonuniform magnetic field inevitable in any toroidal device.

▶ MHD stability theory predicts that RFPs should achieve significantly higher values of β (plasma pressure/field pressure) than tokamaks. The power output of a reactor increases as β^2. RFPs are expected to achieve β as high as 20%. Such high β might permit the use of non-tritium fuel cycles.

▶ The large toroidal field required for tokamak stability puts great mechanical stress on the field coils. In RFP machines, the magnetic field is very small at the coils.

Harold Furth, director of the Princeton Plasma Physics Lab, told us that tokamaks and RFPs both suffer the serious inconvenience of being pulsed rather than steady-state devices. The fact that tokamaks no larger than ZT-40 easily achieve plasma stability for periods of a second, he explained, leads one to expect that tokamak reactors could operate with longer stable pulses than RFPs. It is however quite possible, he added, that both configurations could evolve into steady-state reactors through the use of radio-frequency plasma heating.

History. An early "z pinch" torus was built at Los Alamos in 1952. Wistfully named "Perhapsatron" by George Gamow, it was a pure z-pinch device—the plasma being confined only by the poloidal magnetic field generated by the plasma current itself (flowing in the toroidal or z direction). Because such an arrangement was found to be highly unstable, people began adding modest toroidal field components by means of external coils.

In 1958 Marshall Rosenbluth (then at General Atomic, San Diego) predicted that such instabilities could be reduced by reversing the toroidal field at the edge of the plasma. Such an effect was indeed seen experimentally five years later at General Atomic. Externally imposed field reversal in a z-pinch torus was found to reduce plasma turbulence significantly. But not until the following year (1964) was a quiescent period of actual plasma stability produced in a z-pinch device—the Zeta machine at Harwell. Zeta was the largest toroidal machine of its day. Its minor diameter of 1 meter dwarfs that of today's ZT-40 (40 cm). Under certain conditions of toroidal field and plasma current, the plasma became quiescent and stable for periods of about a millisecond. These quiescent phases were accompanied by the spontaneous reversal of the toroidal magnetic field near the plasma edge.

This phenomenon was not clearly perceived at the time, and in fact Zeta was shut down in 1964—regarded as something of a failure—when the British magnetic-fusion effort moved from Harwell to Culham. Not until after the shutdown did analysis of the old data reveal these quiescent periods. Even then the spontaneous field reversal was not understood theoretically until J. B. Taylor (Culham) showed in 1974 that such reversed field configurations are in fact minimum-energy equilibrium states of the plasma–field system. Taylor's theory revived worldwide interest in reversed field pinches in the mid 1970s, despite the brilliant successes of tokamak efforts during this period.

The first RFP experiments after Zeta, at Culham, Los Alamos and somewhat later at Padua and the Electrotechnical Laboratories outside Tokyo were quite small, and it was generally intended to impose field reversal on them, rather than letting the field reverse itself spontaneously as had happened in the Zeta. This is done by suddenly reversing the current in the external field coils at a certain point in the plasma current buildup.

It was thought that such "programmed field reversal" would require very fast rise times, on the order of a few microseconds, to avoid instabilities before reversed-field configuration was achieved. Because magnetic fields cannot penetrate even highly resistive metals at such speed, these RFPs were all constructed with insulating vacuum liners. It turned out however that these devices were not able to reproduce the millisecond quiescent periods of the old Zeta.

At first it was believed that the failure of these experiments to achieve longer periods of plasma stability was due to their small size relative to Zeta. But then two years ago, the second Eta–Beta machine at Padua succeeded in attaining a quiescent stable plasma for about a millisecond, with a minor diameter of only 25 cm. The trick appeared to be the replacement of the quartz vacuum liner of the Eta–Beta II by a highly resistive metallic liner. This required much longer rise times—100 microseconds—but it achieved periods of field reversal and low turbulence on the order of a millisecond.

The Los Alamos ZT-40 group, led by Joseph DiMarco, Don Baker and Keith Thomas, learning of the Padua success, quickly replaced their ceramic liner by an ultra-thin metallic vacuum liner of highly resistive metal last winter. Almost overnight, Baker told us, that change wrought an extension of quiescent plasma stability from 100 microseconds to 3 milliseconds. The 17-year-old success of the Zeta had been reestablished, but this time with a much smaller machine, capable of far higher plasma current densities. The ZT-40, with a minor diameter of 40 cm and a major diameter of 2.3 meters, has a plasma current capacity of 600 kiloamps.

Running at the moment with a plasma current of only 250 kA, the ZT-40 has already attained electron temperatures of 150 eV—extremely modest when compared with tokamaks of the same size, but comparable with the much larger Zeta. Furthermore, Baker is encouraged by the fact that temperatures and quiescent time periods appear to be scaling favorably with increasing plasma current. The longest stable periods of plasma quiescence—8 msec—were achieved in the ZT-40 by augmenting the transformer induction of plasma current with the discharge of a large, slow capacitor bank to make up for losses. The reversed field is sustained well during this extended period, Baker told us.

The reversal of the toroidal field in ZT-40 is at present accomplished by a hybrid technique of programmed and spontaneous reversal referred to as "aided reversal." The group plans to study wholly unaided field reversal in the near future. This would be the ideal mode of operation for an RFP reactor, Baker told us. "But we'll have to see which technique results in the lowest start-up losses."

The proposed British RFX, with dimensions somewhat larger than Zeta, will have a plasma current capacity of 2 megamps—comparable to that of General Atomic's Doublet III—the highest-current tokamak now in operation. Tihiro Ohkawa and his colleagues at General Atomic are also developing a variation on the RFP. Their Ohmic Heating Toroidal Experiment, it is hoped, will produce plasma stabilization equivalent to field reversal by twisting the external field coils into a helical configuration that produces a highly sheared magnetic field, somewhat in the manner of a stellarator (PHYSICS TODAY, August 1980, page 17). The Ohmic Heating Toroidal Experiment began operating in March. Ohkawa told us that it has already achieved quiescent periods of a few milliseconds. —BMS

A tandem mirror in place at MFTF

Testing is scheduled to begin this month on the first of two gargantuan superconducting magnets that will plug the ends of the tandem Mirror Fusion Test Facility at Livermore. When construction of the 375-ton magnet was begun three years ago, it was intended to serve as a single-mirror machine. But in the wake of a successful small-scale tandem-mirror experiment at Livermore, it was decided last year to expand the MFTF into a tandem mirror machine, MFTF-B (PHYSICS TODAY, October 1980, page 17).

In the tandem configuration, a central solenoid 30-meters long will be plugged at each end by a mirror machine. Thus the magnet just completed will require a mate for the other end. Winding of the second magnet will begin at Livermore this Fall.

Each mirror machine has a quadrupole field produced by a pair of "yin-yang" coils, shaped roughly like the outline of a pair of cupped hands. (The reference is to the traditional Chinese symbol signifying the duality of all things.) The maximum field between the coils will be 40 kilogauss.

Our cover this month shows the first yin–yang pair shortly after its completion in May at Livermore, where the superconducting niobium–titanium coils were wound. The massive stainless steel covers were produced by the Chicago Bridge and Iron Company. A welder is seen joining the two covers to enhance the stabilization of the yin–yang shape against the enormous magnetic stresses to which it will be subjected. The steel covers will be festooned with liquid-nitrogen baffles to shield the magnet, operating at a temperature of 4.2 K, against thermal radiation from the walls of the vacuum vessel. The magnet tests will be conducted inside the evacuated vacuum vessel.

The MFTF-B, scheduled for completion in about four years, is intended to reach ion temperatures of 2×10^8 K and a confinement parameter (particle density $\times$ energy confinement time) of about 5×10^{13} sec/cm^3, comparable to what is expected from the generation of large tokamaks now under construction. With a deuterium–tritium plasma, these conditions would suffice for "scientific-breakeven" fusion; but the MFTF-B will employ only hydrogen and deuterium. The purpose of the experiment will be to study plasma confinement and heating in a large tandem-mirror configuration rather than the fusion process itself. The estimated cost of the facility is about $226 million (1980 dollars). —BMS

Chinese-American project studies earthquake motion

Although earthquakes are an all-too-frequent phenomenon, good data on strong ground motion near the epicenters of major earthquakes are scarce. Such data are crucial for understanding the energy-release mechanisms of strong earthquakes. With better understanding of the seismic mechanisms comes the possibility of earthquake prediction, and guidance for earthquake-resistant structural design.

American and Chinese seismologists have recently undertaken a joint venture for extensive measurement of strong earthquake motion in the seismically active Beijing–Tianjing region of northern China. With a $350 000 grant from NSF, an array of about 35 ground-motion measuring instruments will be installed over the next two years in this region, where six major quakes have occurred in the last fifteen years. The NSF Earthquake Hazard Mitigation Program will fund the purchase of the strong-motion measuring instruments, and the Chinese State Seismological Bureau will install and operate the array.

The principal American investigators are Wilfred Iwan (Caltech), David Boore (US Geological Survey) and Ta-liang Teng (University of Southern California).

The aim of the joint project is to obtain systematic ground-motion data for strong earthquakes. An important feature of the array will be its mobility. In response to seismic events or indications, the individual instruments can be easily uprooted and redeployed. In this way, the mobile array can gather information about earthquakes with different types of fault-break and energy-release patterns under a variety of geological and soil conditions.

Although there have been several accurate predictions of large quakes in China, relatively few strong-motion records have been obtained to date. The Beijing-Tianjing region is among the most seismically active on Earth. The devastating 1976 Tangshan earthquake registered 7.8 on the Richter scale. The scarcity of strong-motion data from China and many other seismically active countries is attributed in part to the unavailability of adequate strong-motion measuring instruments. The 1978 International Workshop on Strong Motion Earthquake Instrumentation Arrays, sponsored by NSF and UNESCO, assigned high priority to cooperative international efforts to install such arrays.

The Workshop selected 28 promising sites throughout the world for the deployment of strong-motion instrument arrays. Since the Workshop, major earthquakes have occurred at or near four of the selected sites—in Japan, Iran, Mexico and Alaska. A number of Chinese seismologists studying past cycles in the Beijing–Tianjing area anticipate an earthquake even larger than the 1976 Tangshan disaster in the near future. □