that the weaker dependence seen may indicate the predominance of some mechanism other than the one Thouless assumed.

Another experiment to test the Thouless prediction had been undertaken[4] earlier by Gerald J. Dolan and Douglas D. Osheroff at Bell Labs, using high-resistivity thin metal film strips at temperatures as low as 10 mK. They saw exponential increases in resistance at low temperature for films with sufficiently high sheet resistances and in some one-dimensional films with low sheet resistances and small film widths. They suspect this behavior indicates one-dimensional localization, but their results are uncertain because their films were not uniform but rather granular.

More experimental work is presently underway at IBM, where Alec Broers, Praveen Chaudhari, Robert Laibowitz and Hans Habermeier (on leave from the Max Planck Institute in Stuttgart) are using high-resolution electron-beam lithographic techniques to make small wires of varying length, and diameters of around a few hundred angstroms. Chaudhari and Habermeier have completed measurements on amorphous alloys of tungsten–rhenium, which show the same temperature dependence seen by the Yale group. The data exhibit magnetic-field effects not yet addressed by theory and give evidence for unusual length dependence, as predicted by Thouless, but in a different form than expected.

Two-dimensional studies. Abrahams and his colleagues pursued the ideas of Thouless beyond the one-dimensional case. They used a scaling theory of localization with only one parameter—a generalized, dimensionless conductance, $g = G/(e^2/\hbar)$, where G is the conductance of some small sample whose sides are of length L. (By contrast, scaling theories of critical phenomena usually require several parameters.) In two dimensions this conductance was found to cross over smoothly from logarithmic or slower to an exponential decrease with L. Thus a sharp, universal minimum metallic conductivity is never reached. Many others have tried scaling theories, and Anderson mentioned that one by Franz J. Wegner (Heidelberg) had similar results except in two dimensions, but none had consistently adopted only one parameter throughout.

William McMillan (University of Illinois) has developed another one-parameter scaling theory of generalized dimension. He makes some quantitative predictions in three dimensions that appear to have been confirmed by experimental work by Jack Mochel and Brian Dodson (also at the University of Illinois) and Robert C. Dynes of Bell Labs.

The scale parameter chosen by the "gang of four" was one originally suggested by Thouless. The parameter is a measure of the fluctuation in energy levels caused by replacing periodic by antiperiodic boundary conditions, compared to the mean spacing in energy levels. The argument goes that sensitivity to boundary conditions is an appropriate criterion for distinguishing localized from extended behavior: If an electron can "see" the boundary it must be in an extended state, and the conductivity of a small hypercube of length L will be governed by its boundary conditions. Scaling is the piecing together of many such hypercubes, with subsequent alteration of the boundary conditions.

Patrick Lee, also of Bell Labs, has tackled the same problem by implementing the renormalization-group approach numerically.[5] By fitting together successively larger groups of blocks, and diagonalizing the Hamiltonian each time, he can arrive at reasonable sample sizes within a few iterations. He has calculated the scaling function for the conductance and agrees with the Rutgers–Bell–Princeton team in the localized limit (corresponding to strong disorder) but fails to obtain the logarithmic dependence on scale size in the limit of weak disorder. Lee believes that his results raise questions about the assumption of one-parameter scaling in the "gang of four" theory. He agrees, however, that the idea of logarithmic localization is receiving increasing experimental support.

The experimental support for the theory by the Rutgers–Bell–Princeton group first came from the study done by Dolan and Osheroff originally to test the one-dimensional predictions by Thouless. Most of their samples seem to be two- rather than one-dimensional. (One common criterion for one dimension is that the width be small compared to the inelastic scattering length, so that an electron is likely to "see" the side. This distinction is only as good as the estimates of scattering length, however.) In their two-dimensional samples, Dolan and Osheroff observed unexpected logarithmic variations of the resistance with both temperature and applied electric field for strips whose sheet resistance was *less* than 10 kilo-ohms per square—the "metallic" regime where constant resistance is usually expected. (See the figure.)

In other work at Bell Labs, David J. Bishop, Daniel C. Tsui and Dynes reported some preliminary results on MOSFET devices at the conference on electronic properties of two-dimensional systems last month in Japan. To ensure that their results are not affected by defects in the oxide layer, which in turn affect electron mobility, these researchers examined eight devices with a wide range of mobilities and found they all exhibited the same behavior of resistance as a function of temperature. They have observed the logarithmic dependence of resistance on temperature with a slope that increases as the resistance increases up to 10 kilo-ohms per square. Dolan told us that the agreement in the results from the two Bell experiments is remarkable evidence of the generality of this kind of behavior. Dynes pointed out that with the MOSFET they are able to get better statistics and determine the slope of conductance versus log T to be about 0.5, but the value that would be expected theoretically is not yet well understood. Dynes also commented that they have reexamined earlier data from quench-condensed thin films and found the same logarithmic behavior. The weak increase in resistance had previously been hidden because the data were plotted on an exponential scale.

Translating from the log dependence on scale predicted by theory to the log dependence on temperature and field observed in the lab is not a straightforward matter, especially as the theory is valid for $T = 0$ K while experiments are at finite temperatures. The concepts of Thouless provide some guidance. Essentially he suggests that the effective length scale, to which measurements of conductivity would be sensitive, is the inelastic scattering length, which in turn is a function of temperature. Adopting similar concepts, Anderson, Abrahams and Ramakrishnan have written a paper[6] directly addressing the interpretation of the log-T behavior in the Dolan and Osheroff experiment. To explain the logarithmic dependence on electric field, they suggest ohmic heating of the electrons. Thus the experiments, first stimulated by theory, are in turn challenging the theorists to reach a still deeper understanding of scattering and other behavior of disordered systems. —BGL

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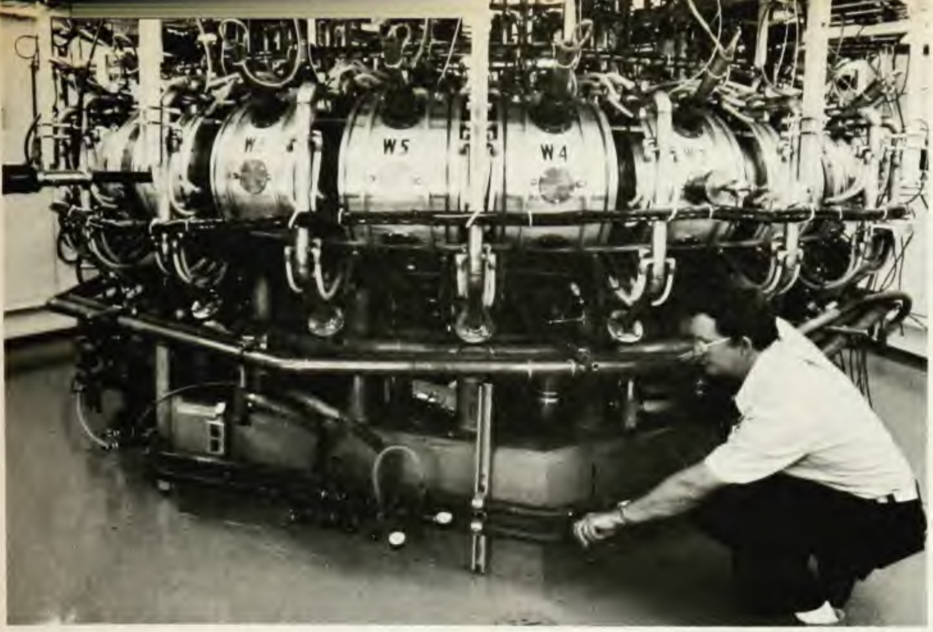
Proof-of-principle test for Elmo Bumpy Torus

We don't know whether he named it after St. Elmo's fire, or after his clever Uncle Elmo. Ray Dandl, who guided the evolution of the Elmo Bumpy Torus over the last two decades at the Oak Ridge National Laboratory, won't tell. The Elmo Bumpy Torus is something of a hybrid between toroidal and mirror fusion-reactor designs. Last October, a Department-of-Energy Concept Review Com-



The Oak Ridge Elmo Bumpy Torus is a toroidal chain of 24 magnetic-mirror segments. Each segment is also a microwave cavity, in which 28-GHz radiation generates a plasma-stabilizing relativistic electron ring. Bob Livesey, head of EBT operations at Oak Ridge, is at right.

mittee chose the EBT concept from among nine magnetic-confinement alternatives to tokamaks and mirrors, to be supported for a proof-of-principle test. Early this year the DOE Office of Energy Research concurred in the choice of the Elmo Bumpy Torus, and Oak Ridge is at present conducting a design competition among four industrial consortia for an EBT proof-of-principle facility, which is expected to be ready for experiments in about 1984. Aside from the Oak Ridge machine, the only other such bumpy torus currently in operation is in Japan.

The tokamak has come closer than any other magnetic plasma-confinement device to the conditions necessary for thermonuclear ignition, but the viability of the tokamak concept for useful reactors has been called into serious question. Last year, the Ad Hoc Experts Groups on Fusion (see PHYSICS TODAY, September 1978, page 85), headed by John Foster of TRW, emphasized that the complexity inherent in the tokamak design may lead to serious engineering obstacles to the production of commercial reactors. In its report to the DOE, the Group warned against excessive reliance on the tokamak before its engineering feasibility has been established, and it recommended that a few of the most promising alternative schemes be supported to the level of providing real tests of their potential.

James Decker of DOE, who headed the Concept Review Committee, enumerated for us some of the engineering problems of the present-day tokamak design that are not shared by the Elmo Bumpy Torus. The elaborate system of interlocking current coils in the tokamak would seem to rule out modular construction. The necessarily small "aspect ratio" (major/minor radius) of the tokamak torus makes access to the central hole of the doughnut difficult, both for heat removal and maintenance. Others have pointed out that the small aspect ratio also requires the coils in the center to be in close proximity to one another, subjecting them to very high magnetic forces. Because the toroidal plasma current in a tokamak is driven by transformer action, it operates in a pulsed mode. Such a pulsed cycle subjects the reactor to significant thermal and mechanical stresses that would not occur in a continuous-mode device like the Elmo Bumpy Torus. Decker emphasized however that potential solutions to all these engineering problems are being actively investigated within the current tokamak design. He expects that the tokamak will become increasingly attractive as a realistic reactor design.

The Elmo Bumpy Torus currently in operation at Oak Ridge, the EBT-S, is essentially a ring of 24 magnetic-mirror segments in series, with a toroidal major radius of 150 cm. The mirror segments are produced by 24 current coils of 20-cm bore, wound at equal intervals around the minor circumference of the torus. The toroidal vessel is bumpy because in the center of each mirror segment, between adjacent coils, the minor diameter expands to 28 cm, corresponding to the bulging of magnetic field lines between the mirror coils.

In a simple mirror (two parallel coils), the plasma particles heading toward the ends (the coils) are reflected back toward the middle by the convergence of the magnetic field lines toward the coils. But there is inevitable leakage out the ends of the mirror. In the EBT, such escaping plasma simply enters the adjacent mirror segments. The simple mirror is also subject to a virulent magnetohydrodynamic instability. Although the confining field increases toward the ends, it decreases from the center in all directions normal to the coil axis, giving rise to an unstable equilibrium that can promptly expel the plasma out the sides of the mirror. Simple toroidal machines fail to confine plasmas for much the same reason, because the toroidal magnetic field decreases in the radial direction, encouraging the plasma to fall outward.

Various remedies exist for dealing with the MHD plasma instability. In the case of mirror machines, in 1964 M.S. Joffe and his colleague at the Kurchatov Institute in Moscow were the first to eliminate the MHD instability. They did it by distorting the shape of the mirror coils to produce a "magnetic well" (a minimum at the center of the mirror field). The tokamak deals with the toroidal confinement problem by having a toroidal current induced in the plasma, which distorts the field lines into helices (see PHYSICS TODAY, May 1979, page 25).

Microwave-induced electron rings. In 1964 Dandl and his colleagues were experimenting with radio-frequency heating of the plasma at the electron cyclotron frequency in a single-mirror device—the original Elmo (not yet a torus). They were surprised to find that the gyrating electrons formed themselves into a large relativistic annular ring, parallel to the coils, in the midplane of the mirror. The net current of the ring vanishes, because the electrons continue to gyrate in tight little circles about the field lines as they go around the annular ring, producing a diamagnetic double current layer. But this electron current configuration has the happy effect of distorting the mirror field to produce a magnetic well at its center—just what's wanted for MHD stability.

The original Elmo consisted of two parallel mirror coils placed in a microwave cavity to produce the annular ring that heated the plasma and created the stabilizing magnetic well. With a view to an eventual toroidal chain of such microwave-heated mirrors, the group studied how far one could cant the mirrors without losing stability. (In the EBT-S the 24 coils are 15° off parallel with their nearest neighbor.) The first Elmo Bumpy Torus (EBT-1) was completed in 1973, with each mirror embedded in a cavity that fed the plasma microwave energy at 18 GHz, the electron cyclotron frequency corresponding to the 6.5-kilogauss mirror field.

Simple toroidal machines suffer yet another mode of particle loss. The orbits of charged particles of opposite sign tend to separate and wander out the top and bottom of the torus. Therefore toroidal equilibrium requires that the particles be made to circulate about the minor axis. In the tokamak this is accomplished by the helical twisting of the field lines. The EBT achieves the same result without a toroidal plasma current. The large radial field gradients resulting from the bumpy torus configuration cause the particles to drift in the azimuthal direction.

To achieve thermonuclear ignition, a deuterium–tritium plasma must ultimately attain an ion temperature of 10 keV (about 10^8 K), and the product of the density and the energy confinement time must be greater than 3×10^{14} sec cm^{-3}. John Sheffield, who heads the magnetic-confinement experimental program at Oak Ridge, pointed out to us that as the density is increased one must raise the frequency of the microwave radiation, because the lower frequencies will be reflected without absorption as the density increases. Last fall the Oak Ridge group began a new phase of EBT operation (EBT-S) with the introduction of gyrotrons, developed by Varian Associates, that should ultimately deliver 200 kW of continuous microwave power at 28 GHz. With this frequency increase, the field strength was raised to 10 kG to maintain cyclotron resonance. The delivery of so much microwave power at such high frequencies has presented significant engineering problems, and Oak Ridge is working in collaboration with Varian to improve the stability of the gyrotrons and ultimately to raise the frequency of the gyrotrons.

In its current phase, the EBT has achieved values of the confinement parameter (density × energy confinement time) up to 10^{10} sec cm^{-3}, with energy confinement time around 5 msec. Sheffield told us that 10^{10} sec cm^{-3} is "quite competitive" for a machine of Elmo's present size. Typical temperatures in the EBT plasma are currently 300 eV for electrons and 60 eV for ions.

The highest value of the confinement parameter obtained to date in tokamaks is 3×10^{13} sec cm^{-3}, achieved by the Alcator at MIT, but the Princeton Large Torus has attained 10^{12} sec cm^{-3} at a significantly higher temperature (7 keV). Decker told us that the objective of the proof-of-principle design (EBT-P) will be to produce an Elmo Bumpy Torus whose plasma parameters are comparable to those of present-day tokamaks. In that regime one should be able to make a realistic test of the physics viability of the EBT concept.

The energy confinement time, 5 milliseconds for the EBT-S to date, is the time-decay coefficient for the rate at which the plasma would lose its energy to the walls in the absence of an external energy source. It should not be confused with the maximum time for continuous operation of the EBT. The toroidal plasma current necessary for the stability of a tokamak is induced by the transformer action of an external current, increasing with time. Such a transformer must eventually run out of volt-seconds; so the tokamak must operate in a pulsed mode, with pulse times ultimately reaching hours at best. The EBT requires no such toroidal plasma current, its MHD stability being achieved by the microwave-generated annular electron rings. The EBT can therefore run continuously. Sheffield told us that the Oak Ridge machine has already achieved many hours of continuous operation. He regards it as impressive that in such continuous operation at high temperature the EBT plasma has achieved equilibrium with contaminants evaporated from the walls, at a tolerably low impurity level. Electrostatic fields at the edge of the EBT plasma present a potential barrier against the excessive penetration of contaminants into the plasma.

At present the EBT plasma is heated only by microwave radiation at the electron cyclotron frequency. It is intended however that EBT-S and the next generation EBT currently under design will also make use of the lower ion cyclotron frequency, and neutral-beam heating. The only other bumpy torus currently in operation, in Nagoya, Japan, is very similar to the present Oak Ridge machine.

Although Oak Ridge has been chosen to supervise the proof-of-principle design competition—among four consortia, headed by Westinghouse, Grumman, McDonnell-Douglas and Ebasco—the ultimate site of the EBT-P has not yet been chosen. At the Concept Review last fall, Oak Ridge was joined in its advocacy of the Elmo Bumpy Torus by TRW and McDonnell-Douglas, the latter presenting an independent conception of a bumpy torus somewhat different from that of Oak Ridge.

Reversed field pinch. Decker told us that the EBT's closest competitor among the nine alternative concepts presented to the Review Committee last October was the reversed-field-pinch concept, advocated by Los Alamos. The Committee judged the competing concepts by two principal criteria: Is the concept at a sufficiently advanced stage to be ready for a proof-of-principle test by the mid-1980's, and does it promise significant advantages over tokamaks and mirror machines? Decker and his colleagues on the committee concluded that the reversed field pinch was indeed at a sufficiently advanced stage of development, but that in its similarity to the tokamak it offered fewer potential advantages than did the Elmo Bumpy Torus. Like the tokamak, reversed-field-pinch machines would have to be operated in a pulsed rather than a continuous mode. —BMS

High-capacity buried power lines

With the growth of metropolitan areas and their demand for electric power, it is becoming increasingly difficult to transport adequate electric power to such centers by conventional transmission lines. Several recent studies have concluded that by the end of the next decade it will be hard to make do without installing high-capacity underground cables to transport power to the central cities. Overhead lines are in many ways unacceptable in built-up areas, and conventional underground cables have insufficient carrying capacity.

In an attempt to increase the capacity of underground cables, Brookhaven, Los Alamos and several European groups have been designing and testing superconducting transmission cables. Nonsuperconducting attempts at increasing underground cable capacity are also under active study. These include increasing the conductivity of conventional conductors by liquid-nitrogen cooling, insulation by electronegative gases, and removal of excessive cable heating by forced circulation of oil or water.

A three-phase overhead transmission line has a maximum carrying capacity (at 765 kV) of about 3 gigawatts, adequate for the needs of a population of about three million people. According to Thomas Garrity of the Department of Energy, which is funding much of the work on high-capacity underground transmission, one is not at present looking for cables to carry more than about 3 GW. To carry more than this in a single line would make a large population area dependent on the integrity of a single channel. What is wanted is an underground cable with a power capacity that can match the best overhead lines. A superconducting cable could presumably carry 3 GW at a much lower voltage than the 765 kV required by overhead lines. An extensive 1977 study by the Philadelphia Electric Company forsees the need for 4- or 5-GW cables by the end of the next decade.

High-voltage overhead lines require a wide right-of-way (290 feet for a 765-kV line). This wide swath can still be used for agriculture, but not for housing or other urban or suburban activities. It is increasingly difficult for utilities to acquire such rights-of-way near cities. Land is scarce, and there is concern, as yet unproven, that 60-Hz radiation from high-tension lines may be damaging to health. Even in open country, opposition is increasing to overhead lines, on aesthetic grounds. It has also been suggested that the ozone generated in overhead coronal discharges has an adverse effect on livestock and crops.

A conventional underground cable, with oil and paper insulation, is limited to less than 500 MW. This is quite adequate for secondary distribution systems in urban areas, but a serious limitation for primary transmission lines. The principal sources of this limitation are heat dissipation, high capacitance and high-voltage insulation. It is difficult to dissipate the ohmic heat in the confined space of an underground trench three or four feet wide, where temperatures become dangerously high as one attempts to push up