July 1975 Frederic H. Coensgen, W. F. Cummins, B. G. Logan, A. W. Molvik, W. E. Nexsen, T. C. Simonen, B. W. Stallard and W. C. Turner produced[1] a stable plasma up to 13 keV mean ion energy (a mixture of energies 9–18 keV). Their value for $n\tau$ was 7 (−2,+5) × 10^{10} cm^{-3} sec.

The experimenters had managed to stabilize the drift cyclotron loss-cone instability, first discussed theoretically in 1965 by Marshall Rosenbluth (Institute for Advanced Study) and Richard F. Post (Livermore). In this mode, the instability occurs because low-energy ions are missing. In 1967 Post suggested that by supplying the missing portion of the ion population, the plasma could be stabilized. In the 2XIIB experiment, the amount required was only about 1% of the density.

The technique they used was to supply cold plasma from a gun, shooting the stream along the magnetic-field lines; the gun operated in a low-voltage, long (millisecond) pulse mode. The cold plasma is automatically warmed by the instability fluctuations themselves to a temperature that quenches the noise in the system.

Being able to produce and maintain a dense, energetic plasma in a steady-state magnetic-mirror field has been a major problem. Last October, in a second experiment, Coensgen and his collaborators found[2] that the streaming plasma used previously for stabilization would also serve as a suitable target plasma for neutral-beam injection in a quasi-dc magnetic field. Thus, the Livermore workers believe they now have a method adaptable to superconducting dc magnets. In this second experiment, essentially the same parameters were obtained as in the July experiment.

In a third experiment, done in February, Coensgen and his collaborators used a gas box beyond the mirrors; this gas box had a small slit, which conformed to the field lines in that region. Plasma streaming through the gas emitted by the box caused the gas to ionize, creating the needed low-energy plasma ions. After the stream is cut off, if the gas box is used, the plasma density, instead of falling off, continues to build up to 1.2 × 10^{14} cm^{-3}, a factor of three or more above earlier values. This level was maintained for as long as the sources could be operated (5 millisec). The volume-averaged plasma beta (the ratio of plasma pressure to external magnetic pressure), as measured with diamagnetic loops and from the cyclotron frequency, is about 0.7 with a peak value substantially above this. As Post explained to us, at the highest operating condition, the Livermore group had an energy density for the plasma comparable to the energy density of the field at the time when the field had decayed to about 5 kG.

Field reversal. Having a high-beta plasma has two advantages in mirror experiments. One is very efficient utilization of the magnetic field—lots of confinement for just a little field. A second factor is that high beta makes the mirror well even deeper than before the plasma was there. This had led Livermore to consider using in the mirror program an approach resembling the Astron concept, developed by the late Nicholas Christofilos. In field reversal, the electric currents within a confined plasma become so intense that they literally reverse the direction of the magnetic field inside the plasma, relative to its direction with no plasma present. In Astron field reversal was to be achieved by trapping a ring of circulating electrons (at many MeV) between mirrors. Although the experiments of Christofilos and his collaborators at Livermore did not actually reach field reversal, experiments at Cornell University, by Hans Fleischmann and his collaborators, who used a different technique, have not only demonstrated that field-reversing (greater than 190%) electron rings can be produced but also that their lifetime can exceed 1.3 millisec.[3] In attempting field reversal with the Livermore mirror, the experimenters would use only the plasma-ion currents.

Field reversal would be one way to improve mirror confinement. Other ways are also being considered. The motivation: to enhance the Q value of the mirror fusion reactor. Q is defined as the ratio of fusion power released to heating power input to the plasma. Within practical limits on the mirror ratio, Q is expected to be 1.0–1.5. Livermore would like to get this value up to 2 or higher; this would still further improve the economic picture for mirror fusion reactors. Another enhancement approach is to apply strong rf fields to the plasma at the mirrors. A third approach is to string mirror cells in series so that ions escaping out the end of an interior cell would have a chance of being trapped again before they reached the end cells.

The proposed MX would be a scaled-up experiment expected to increase plasma temperature fivefold over 2XIIB, to 50 keV, within a factor of two of anticipated reactor requirements. Field strength at the center would be 20 kG, four times that of 2XIIB; coils would be superconducting niobium-titanium. The distance between mirror points would be 3.4 meters. Like 2XIIB the mirror ratio would be 2:1. The vacuum vessel would be 9 meters in diameter. Neutral-beam injection would be provided by roughly two dozen injectors. The device is expected to have the capability to accommodate field reversal if that proves feasible. The primary power supply would be 220 MW, operating quasi-dc, pulsing with a duty cycle of 10%, with a pulse duration up to 30 sec.

Anticipated cost is $94 million, including an office building.

Post anticipates that $n\tau$ would increase by an order of magnitude, to about 10^{12} cm^{-3} sec. For a mirror reactor, which would use direct conversion, one would need $n\tau$ to be between 10^{13} and 10^{14} cm^{-3} sec. MX is roughly the Livermore equivalent of the Tokamak Fusion Test Reactor, now under construction at Princeton University. The TFTR is expected to reach an $n\tau$ of 10^{13} cm^{-3} sec, about an order of magnitude away from that required for ignition operation.

MX has been recommended by ERDA's Fusion Power Coordinating Committee. Rumor has it that Robert Seamans, who heads ERDA, has asked OMB to put MX in the FY 1978 budget. If the President and Congress approve, MX could be doing plasma experiments in 1981.

—GBL

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Electron beams yield high-power microwaves

Over the past ten years intense relativistic electron-beam accelerators (300 kV–10 MV) have been developed that yield 10^4–10^6 amperes/pulse with pulse durations of tens or hundreds of nanoseconds. With this new tool at hand, experimenters have been trying to convert the electron-beam energy into microwaves. By reviving the old devices (travelling-wave tubes and magnetrons) developed a quarter of a century ago and applying the new electron-beam technology, orders of magnitude higher power have been obtained. For example, very recently George Bekefi and Thaddeus Orzechowski (MIT) have produced[1] microwave bursts in the gigawatt range with a conversion efficiency of electron energy into microwave energy of about 35%.

The cyclotron-maser systems developed by Jay Hirshfield (Yale University) and Jonathan Wachtel (Yeshiva University) allow the electron beam to gyrate about a magnetic-field line. Creating a population inversion in the transverse momentum of the electrons provides the free energy needed to drive the instability, causing maser action. This concept was developed further by Victor Granatstein and Moshe Friedman (Naval Research Laboratory) and by John Nation and Yuval Carmel (Cornell University). Granatstein and Melvin Herndon (NRL), Nation and Carmel used this technique in the early 1970's to obtain peak powers of 1 GW for 3-cm (10 GHz) microwaves; efficiency was very low—a few percent. Granatstein, R. Parker and Friedman have also obtained 350 MW peak power at 15 GHz, 10 MW peak power at 8 mm, 2 MW peak power at 4 mm. Granatstein says that these are record peak powers in the millimeter range.

Nation points out that the maximum power-handling capability of the waveguide scales as $1/f^2$ where f is the frequency. If one includes loss terms, the actual power handling capability varies as $1/f^{5/2}$.

A number of Soviet groups have been working in the field since about 1971; at the Lebedev Institute M. D. Raizer, A. Kolomensky, M. I. Petelin, N. F. Kovalev, and Ya. B. Fainberg and Yu. Tkach at Kharkov.

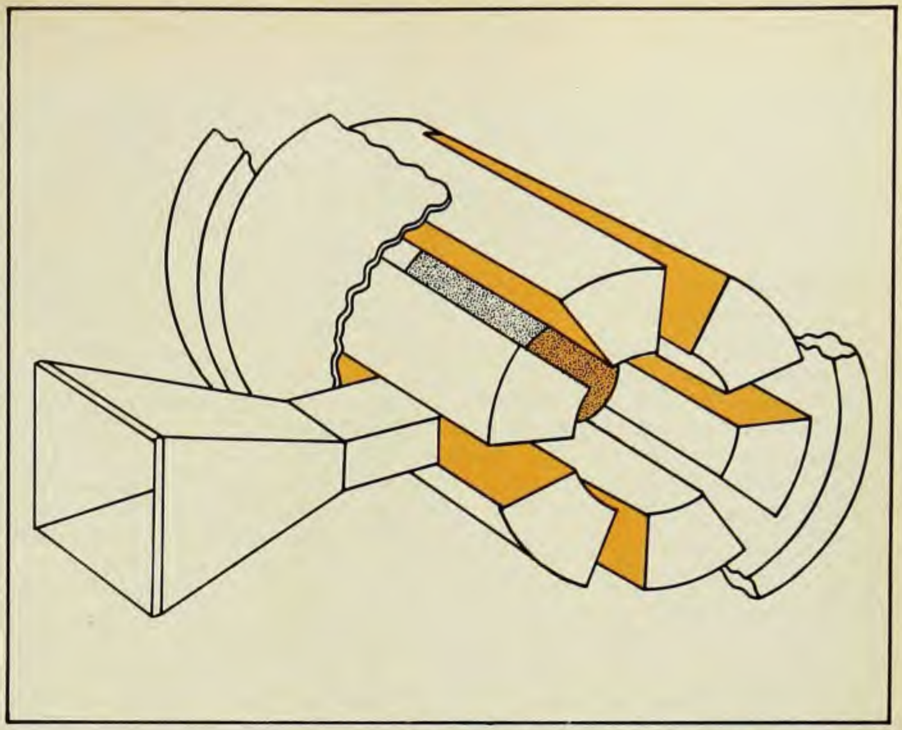
In 1974 Friedman at NRL developed a technique of microwave generation with an automodulated electron beam akin to a klystron. He produced several hundred megawatts at 3 GHz with an efficiency of 15%.

At Cornell, Nation has been working in the area since about 1968. He has experimented with backward-wave oscillators, a type of slow-wave structure. Such a tube, whose walls are rippled, matches the electron velocity to the phase velocity of the electromagnetic wave to allow resonant exchange of energy. Nation points out that such a device is inherently inefficient. Last year the Cornell group used backward-wave oscillators to produce 300 MW at 3 cm with about 10% efficiency. A similar experiment was done at Lebedev.

In new experiments at Cornell, George Providakes, Michael Read and Nation are studying backward-wave oscillators at 30 GHz, using strip-line geometries to enhance power-handling capability. They believe that this technique has application in other microwave-generating devices such as the maser and gyrotron.

A completely different kind of experiment is being done at NRL by Granatstein, taking advantage of the Doppler shift.[2] Using the 2-cm wavelength from a pump source, he counterstreams this electromagnetic radiation against an intense relativistic electron beam. Because of the Doppler shift of the scattered wave, the beam is upconverted in frequency. The resulting wavelength is 400 microns, and the power is 1 MW. These results were to be announced this month at the meeting of The American Physical Society Plasma Physics Division in San Francisco. In other experiments, Granatstein obtained an output wave with twice the power of the input wave. The input was at 3 cm, the output at 8 mm. Theoretical analyses of the coherent scattering mechanisms have been led by Philip Sprangle of NRL.

Another group working at millimeter-wave generation is at Columbia University, where Perry Schlesinger and Thomas Marshall are also trying to go to shorter wavelengths. They have produced 1 MW at 4 mm using a Cerenkov instability of a beam-dielectric-loaded waveguide system. A recent experiment has propagated the electron beam over a region of rippled magnetic field and has developed about 50 kW at 2 mm. Other groups working on microwave generation are Gregory Benford at the University of California at Irvine and H. Doucet at École Polytechnique in Paris.



Relativistic electron-beam magnetron used at MIT to generate gigawatt bursts. The six resonators surround the graphite field-emission cathode. Microwave field at horn exceeds 50 kV/cm.

Magnetron. At MIT Bekefi and Orzechowski's magnetron consisted of a solid cylinder of graphite with a 1.5-cm radius, surrounded by a concentric cylinder of aluminum. Across the 5-mm gap between the two cylinders they applied a voltage of 350 kV. The radial electric field caused field emission at the graphite cathode. Then they applied a magnetic field along the axis of the cylinders. Electrons that would normally hit the anode begin to circulate in Brillouin flow about the axis.

In the outer cylinder are cut a series of six equally spaced resonators, which form a slow-wave structure. The experimenters adjust the velocity of the electron flow until it becomes synchronous with a wave of the structure. The radiation is coupled to the open space outside the magnetron by a flared electromagnetic horn.

The center frequency is 3000 MHz (10 cm) with a bandwidth of a few percent. Efficiency is 35%. Output power was 1.7 G.W.

In August the MIT group went to NRL and joined with Granatstein and Murray Black (George Mason University, Virginia) in attaching the magnetron to a 1-MV source. Preliminary measurements indicate power levels of 4GW. Despite the high value, the experimenters were disappointed—they had expected ten times the power obtained in the earlier work. Now the MIT team is improving its magnetron design.

The NRL and MIT groups are considering using the magnetron output as a pump to strike a second electron beam, taking advantage of the Doppler shift as was done earlier by NRL. They would use two 0.6-MV Febetron accelerators.

Magnetrons may be capable of going to longer pulse lengths. One might be able to go from the presently available 30–100 nanosec pulse lengths to as long as a microsecond, Bekefi believes. The MIT experiments already show the plasma in their diode to be slowed by at least an order of magnitude, he said.

Applications. One major application of the microwave sources is as rf heating for fusion plasmas. Another is to study the nonlinear interaction of the powerful waves with plasmas. This will be useful either for plasma diagnostic purposes or in pellet fusion. There is also some speculation about obtaining pellet fusion using high-power microwaves as the energy source.

Radar applications are of course possible. One area would be in planetary studies, bouncing the microwave radiation off the planet. Another possibility is to use the microwaves for deep-space communications.

Granatstein is excited about the millimeter and sub-millimeter applications. He feels that the electron-beam work offers a unique capability out to 100 microns. The competition is optically pumped molecular lasers, which are inherently less efficient, he says. —GBL

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Proofreading

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Overhauser (Purdue University), had to write a letter of recommendation for the Buckley Prize describing the Overhauser effect. In this nmr effect, electron spins are coupled to nuclear spins. By applying a large microwave signal to the electrons, the nuclei acquire an induced polarization, their population ratio going from a small value to a large one. The system acts as though the energy difference between spin up and spin down is very different from the actual value.

Reasoning that chemical systems can also undergo an Overhauser effect, Hopfield searched for a system of chemical kinetics that could enhance the population ratio of an enzyme, discriminating between two molecular species A and B. If the enzyme were a Maxwell demon, it would wait to act, regardless of what substance was present. This delay would allow B to decay, thus discriminating in favor of A.

So the scheme would require the enzyme E, when reacting with A, to produce an intermediate chemical, AB*, before eventually producing the final product A′. In addition to this time delay, an alternative path in which AE* breaks up into A + E must be included.

The reaction Hopfield postulates is

$$\begin{array}{ccccccc} A + E & \rightleftarrows & AE & \rightleftarrows & AE^* & \longrightarrow & A' + E \\ & & & & \uparrow\downarrow & & \\ & & & & A + E & & \end{array}$$

Then one introduces an energy source (the chemical analog of the Overhauser-effect microwaves) to drive the reaction of A + E going to AE*; this allows one to make AE* a very high-energy compound; so one can make the probability very small of its formation from below.

Having arrived at AE* the system can go forward, or it can abort. The probability of aborting is determined by ΔG. The high-energy intermediate can be formed and discriminate once in a certain ΔG. Then the same ΔG can be used a second time, to decide whether the system will go forward and form A′ or go from AE* to form A + E again. Thus the same kinetic discrimination can be used twice because of the essentially irreversible energy driving source.

The commonest energy source for biological reactions is the hydrolysis of ATP. When AE goes to AE*, at the same time a molecule of ATP hydrolizes, being converted to ADP and phosphate. For all practical purposes, there is very little ADP around; so the reaction cannot go backward. The ATP acts as a driving force on the forward reaction.

What systems use kinetic proofreading? We asked Hopfield. One example is the choice of what base will be added to DNA. In DNA replication there is a chemical reaction that is isomorphic to the kinetic proofreading.

A second application is discrimination in building proteins. The protein is told what it is supposed to be making by a piece of messenger RNA, which consists of a sequence of bases like DNA has. The first three bases specify the first amino acid, the next three the second amino acid, and so on.

A third application is discrimination in using transfer RNA. A particular molecule of transfer RNA recognizes a particular three-letter code word in protein synthesis and must therefore have the corresponding amino acid bound to it, ready for insertion in a growing protein.

To observe experimentally whether or not proofreading occurs, one can look for a one-to-one relation between the amount of ATP used and the amount of A′ formed. After the ATP hydrolysis, if the correct product occurs, the system gets to AE*, and the amount of ATP hydrolized would be comparable to the amount of A′ formed. If on the other hand, an incorrect match occurs, BE* is formed. If effective proofreading is going on, BE* should chiefly be rejected. The ratio of the amount of product formed to the amount of ATP used for the correct material should be near one. For the incorrect material, the ratio should be far different than one. To the extent the ratios differ, they represent the benefit obtained from proofreading.

Because A and B are competing, one has an amount of AE and BE that greatly favors A. When material arrives at AE*, it has already read the enzyme once. Now two paths are available: One goes to the product. The other is a downward path that does not form the product—the exit path for errors in proof. Without the downward path, everything arriving at AE* would belong to A′ + E so that the net accuracy would be the accuracy with which AE* was formed compared to BE*. However, with the downward path, one can throw out most of the time that B is produced. This second discrimination is the proofreading. And the efficiency of the proofreading is found from counting how many times the reaction goes forward compared with the times it goes down.

Experiments. Recently Hopfield and Tetsuro Yamane (Bell Labs) and their collaborators studied[2] the matching of correct amino acids to correct transfer RNA. This matching is done enzymatically—the enzymes first recognize a particular amino acid out of a choice of 20. Then the enzymes must recognize the correct transfer RNA. They found that the discriminations have an error of one in 100 to 400, depending on the system they studied. That is, the system is proofreading on a scale of 1 in 100–400. Combined with an initial reading precision of 1 mistake in 100, the net error rate of 1 in 10^4 for protein synthesis is reached.

Before the Hopfield work, Arthur Kornberg (Stanford University) had found an editing function in DNA polymerase in E. coli. Nancy Nossal (National Institutes of Health) and independently Maurice Bessman (Johns Hopkins University) had studied mutants in bacteriophage, which has its own DNA polymerase that regulates how DNA is copied. These mutants can be qualitatively understood, Hopfield told us, in terms of the kind of mechanistic description that Kornberg gave, but the energetics of discrimination become clear only in terms of the kinetic proofreading scheme.

Other work that preceded Hopfield's was done by Paul Berg (Stanford University). In studying transfer RNA, Berg noted that if the wrong material is formed, in some cases it is rapidly hydrolized by the enzyme. So once wrong matches are made in the solution, they do not persist. Hopfield notes that Berg's experiments and those by Paul Schimmel (MIT), although not actually demonstrations of proofreading, did suggest what systems should be looked at.

Meanwhile, independently and at the same time that Hopfield was doing his work, Jacques Ninio (University of Paris) studied DNA and developed a mathematical formulation[3] isomorphic to the one Hopfield found.

A different example of proofreading was recently studied by Robert Thompson (Harvard Medical School), who studied the recognition of transfer RNA on a messenger ribosome complex. He found a proofreading improvement on a scale of 50–100 in this case. —GBL

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in brief

The latest generation of atomic clock at the National Bureau of Standards has been used to determine the length of the second to within 0.85 parts in 10^{13}, according to a recent Bureau announcement. The NBS determination implies that the international atomic second, maintained by the International Time Bureau in Paris, is too short by about 11 parts in 10^{13}. □