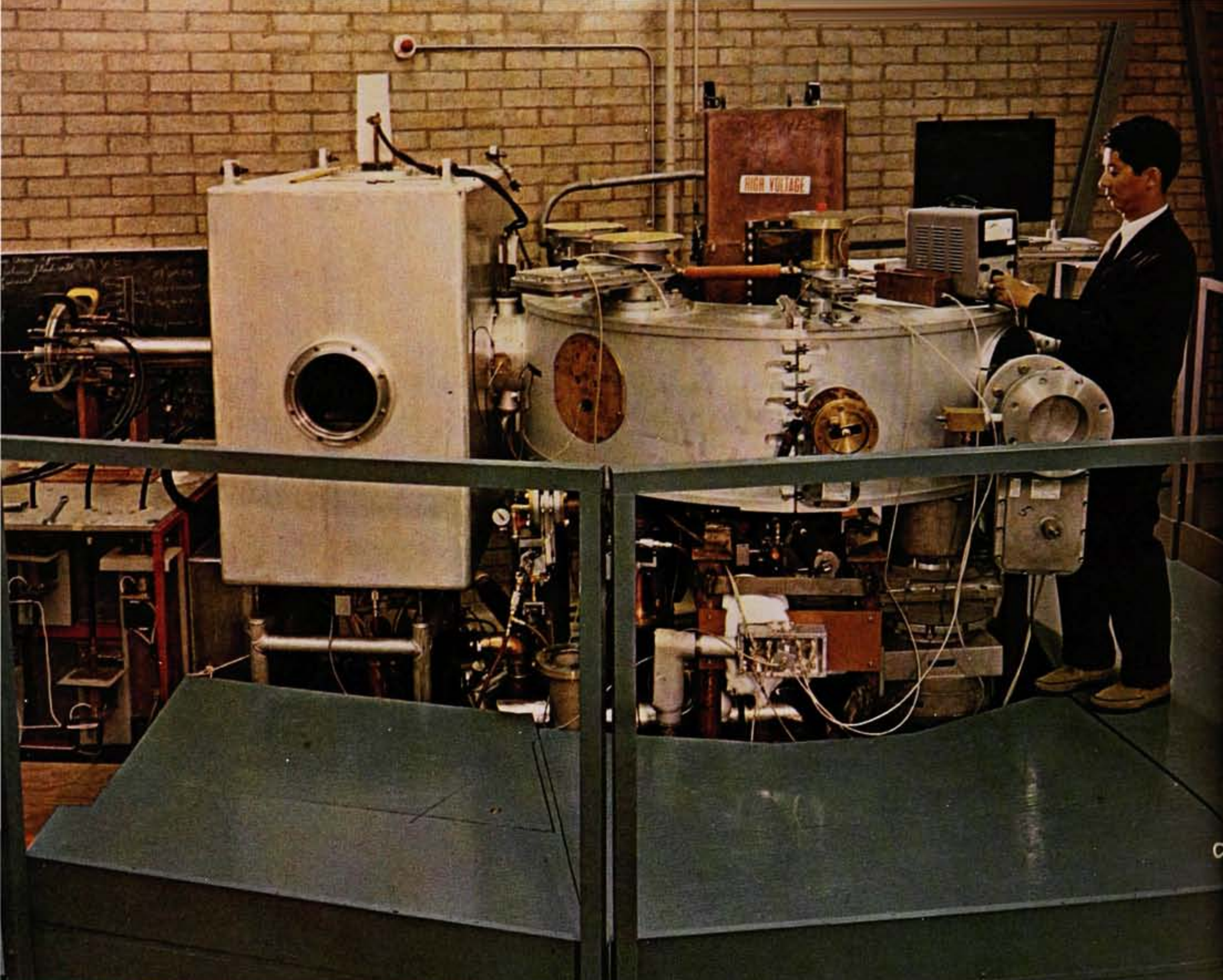
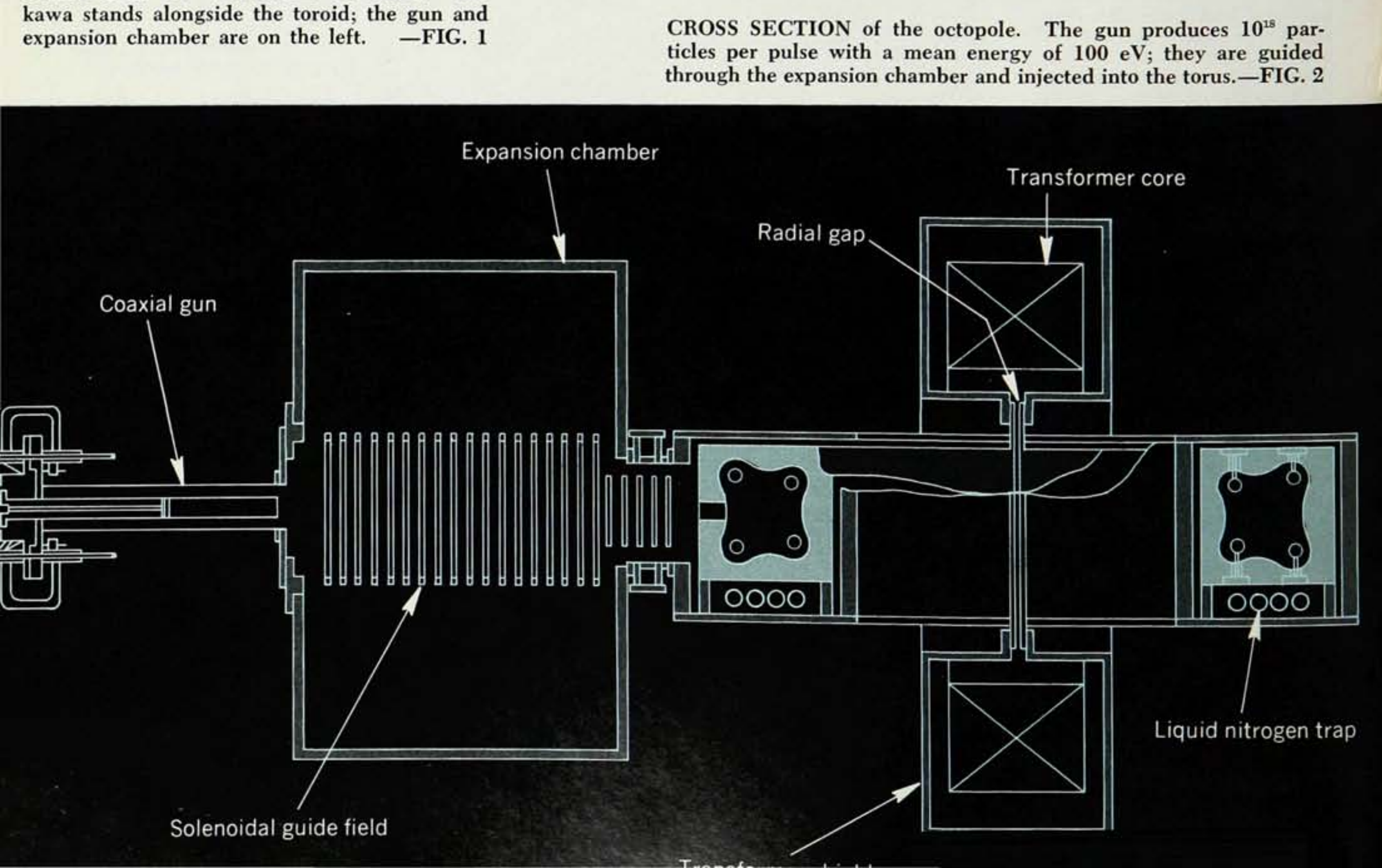


OCTOPOLE AT GENERAL ATOMIC. Ohkawa stands alongside the toroid; the gun and expansion chamber are on the left. —FIG. 1

CROSS SECTION of the octopole. The gun produces 10^{18} particles per pulse with a mean energy of 100 eV; they are guided through the expansion chamber and injected into the torus.—FIG. 2



Plasma Confinement In the Toroidal Multipole

Controlled thermonuclear fusion as a source of power awaits the development of a suitable method of plasma containment. The toroidal multipole system may offer fundamental advantages that are explored in these experiments.

by Tihiro Ohkawa and Norman Rostoker

Plasma confinement systems of various kinds have been studied in many countries for more than 15 years, with the attainment of controlled thermonuclear fusion as the aim. Most of the effort, particularly recently, has been devoted to stellarators; the largest machines are the C Stellarator at the plasma physics laboratory of Princeton University and the Tokomak at the Kurchatov Institute in Moscow. More recently experiments with toroidal multipole devices have shown that the containment time may be at least ten times that for stellarators, by reducing the loss of plasma density through "pump-out" or Bohm diffusion, a turbulence effect that had been the limiting factor of earlier machines.

Stellarators

Usually a stellarator involves a simple coil to produce a toroidal field plus helical multipole windings to produce a rotational transform and magnetic shear (see figure 3). However there are many variations; for example the rotational transform may be produced by a toroidal current in the plasma as in the Tokomak series; it is possible to produce a modest magnetic well with additional windings. We might define a stellarator as a toroidal containment system that does not possess axial symmetry about the major axis and for which $\beta = 8\pi P/B^2 \ll 1$ where P is the plasma pressure and B is the magnetic field strength.

In almost all experiments with stellarators the phenomenon of Bohm diffusion is observed. Low frequency fluctuations in the plasma potential are seen with magnitude

$$\Delta\Phi \approx kT_e/e$$

where T_e is the electron temperature. The containment time is $\tau \approx r_0^2/D$ where r_0 is the wall radius and $D = ckT_e/16Be$ is the Bohm diffusion coefficient. One simple-minded derivation of this coefficient suggests that it is due to fully developed turbulence of the plasma. For example the drift velocity across field lines is given by $V = c\nabla\Phi/B$; $\Delta\Phi \approx kT_e/e\lambda$ where λ is a scale length for the turbulence and the particle current across field lines is thus $nV = D\nabla n = Dn/\lambda$. If we now solve for D, λ cancels and the Bohm formula is obtained, except for the numerical factor.

Bohm diffusion has been observed under a wide variety[1] of conditions; with electron densities 5×10^9 cm^{-3} $< n < 2 \times 10^{13}$ cm^{-3}; with ohmic heating, electron cyclotron heating, ion cyclotron heating, resistive microwave heating, and no heating. Indeed, there is sufficient evidence to speculate that it might be a law of nature for all toroidal systems, in which case a thermonuclear reactor would be impractical. In addition one might conclude that further experiments with toroidal systems will contribute little to plasma physics because it is not possible to identify an instability in the presence of fully developed turbulence.

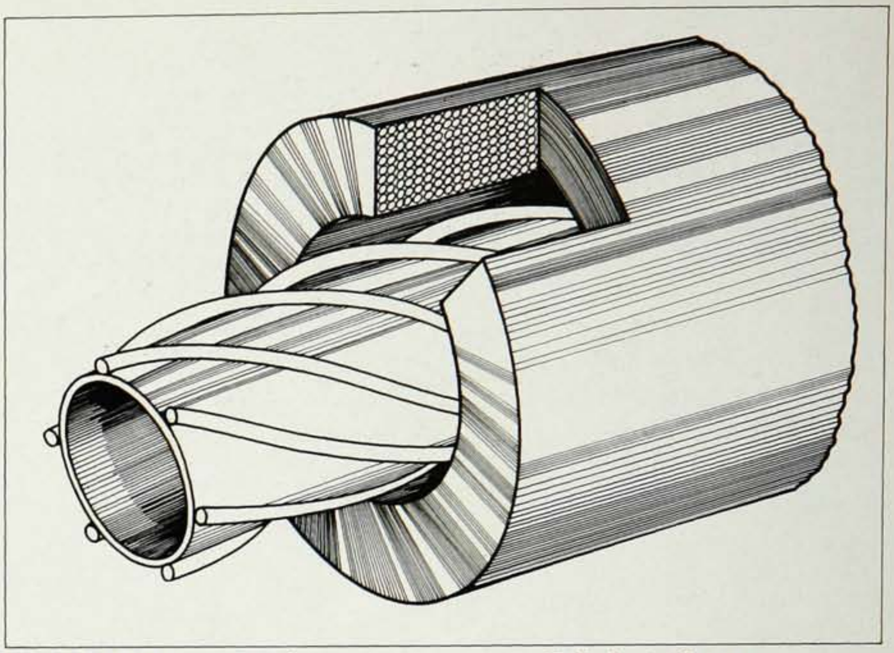
In recent Soviet experiments with the Tokomak[2] a containment time one order of magnitude larger than the Bohm value is claimed. During the past three years experiments have been carried out in Germany with the Wendelstein stellarator.[3] The distinctive feature of this device is that plasma is produced by contact ionization of a beam of cesium atoms that is incident on a hot tantalum plate. Plasma diffusion rates have been observed that are much less than the Bohm rate and are close to the classical rate. The experimental data are very sensitive to small field errors and the precise position of the tantalum plate with respect to the magnetic axis. In a similar experiment with the C Stellerator,[4] only Bohm diffusion has been observed. This experimental evidence obtained with stellarators supports the view that Bohm diffusion is not a law of nature for toroidal systems.

Toroidal multipoles

The distinctive feature of the multipole is that it has axial symmetry about the major axis of the torus. It consists of N internal rings carrying parallel currents in the toroidal direction ($N =$ 2, quadrupole; $N = 4$ octopole, etc.). A conducting wall carries the reverse current (see figure 4). The magnetic configurations with internal conductors were first discussed in 1961 by S. I.

Symbol definitions

- β — ratio of plasma pressure to magnetic field, $= 8\pi P/B^2$
- P — plasma pressure
- B — magnetic field strength
- $\Delta\Phi$ — fluctuations in plasma potential Φ as a result of instability
- — Boltzmann's constant
- T_e — electron temperature
- e — electronic charge
- τ — containment time
- r_0 — wall radius of plasma vessel
- D — the Bohm diffusion coefficient, $= ckT_e/16Be$
- c — velocity of light
- V — drift velocity across field lines or thermal speed
- λ — a parameter with dimensions of length in Bohm diffusion
- n — number of particles (ions, electrons) per unit volume in the plasma
- N — number of internal rings in a toroidal multipole
- Ψ — magnetic flux
- μ_0 — vacuum permeability
- I — current in multipole rings
- B_r, B_θ — tangential and radial components of magnetic field
- U — a parameter defined by $U = \oint B^{-1}dl$, where the integral is taken around closed flux lines
- R — radius of curvature of a field line
- a — defined by $a^{-1} = |\nabla n/n|$
- g — defined by $g = V^2/R$
- V_a — the Alfvén speed, $= B(4\pi nM)^{-1/2}$
- ω — noise frequency
- $k_\perp$, $k_\parallel$ — noise wave number perpendicular and parallel to B
- v_p — noise phase velocity
- J_d — diamagnetic current
- Ω_i — cyclotron frequency (Larmor frequency) for ions



STELLARATOR seen in schematic cross section. Helical windings are located inside the main coils. —FIG. 3

Braginskii and B. B. Kadomtsev.[5]

For simplicity we shall consider the stability properties in terms of a linear octopole for which the field lines are indicated in figure 5. The flux function for this case is

$$\Psi_{r,\theta} = \mu_0 I(4\pi)^{-1} \times \log\,[1 + (r/r_0)^8 - 2(r/r_0)^4 \cos 4\theta]$$

and the fields are

$$B_r = r^{-1}(\partial\Psi/\partial\theta),\ B_\theta = -(\partial\Psi/\partial r).$$

According to the theory of MHD (magnetohydrodynamic) stability[6] a sufficient condition for stability in the limit that $\beta \to 0$ is

$$\nabla U \cdot \nabla P < 0$$

where P is the plasma pressure,

$$U = -\oint B^{-1}dl$$

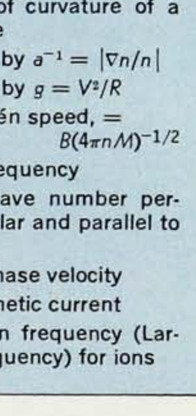
and the integral is taken around closed flux lines. Figure 6 is a plot of U as a function of Ψ. If the plasma can be placed in the trap so that P is related to Ψ as indicated in figure 6, then stability is predicted. U is of the nature of a magnetic "potential" and forms a "mean magnetic well" in which the plasma is contained.

By considering two neighboring flux tubes such that $\delta P < 0$ we can show that the stability condition is

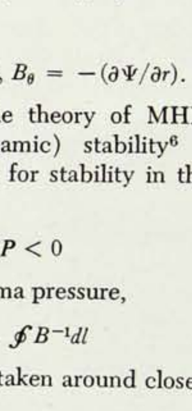
$$\delta U \approx \oint R^{-1}B^{-2}dl > 0$$

where R is the radius of curvature of the field line and is to be counted positive when the line is concave viewed from the low-pressure side. Inside the separatrix R is always positive so that this region is referred to as "an absolute minimum B" region. Outside the separatrix there are regions of positive and negative curvature. The weighting factor $1/B^2$ favors the regions of positive eurvature when $\Psi < \Psi_c$. This type of stabilization is referred to as "average minimum B."

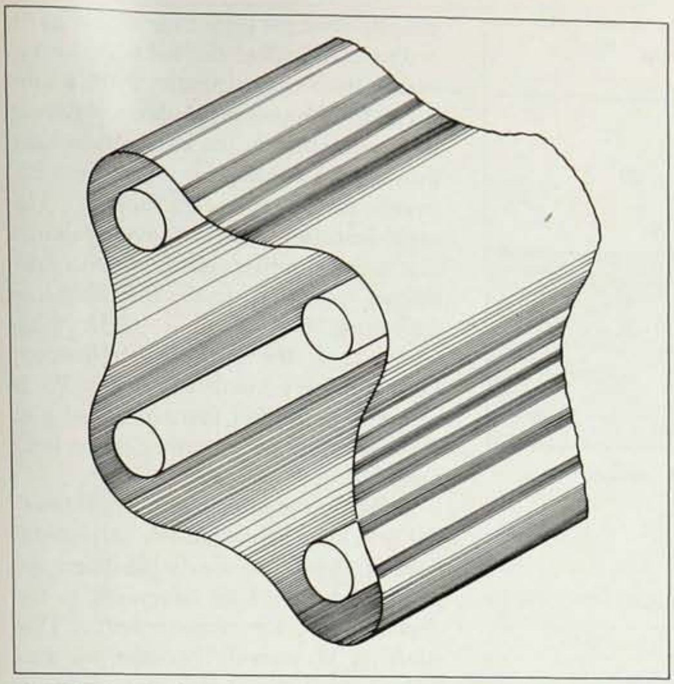
In the regions of negative curvature a flute instability can grow with time constant $\tau \approx (a/g)^{1/2}$ where $a^{-1} = |\nabla n/n|$ and $g \approx V^2/R$ where V is the thermal speed of the ions. The growth will not take place if the communication time between regions of positive and negative curvature $\tau_c = L/V_A < \tau$



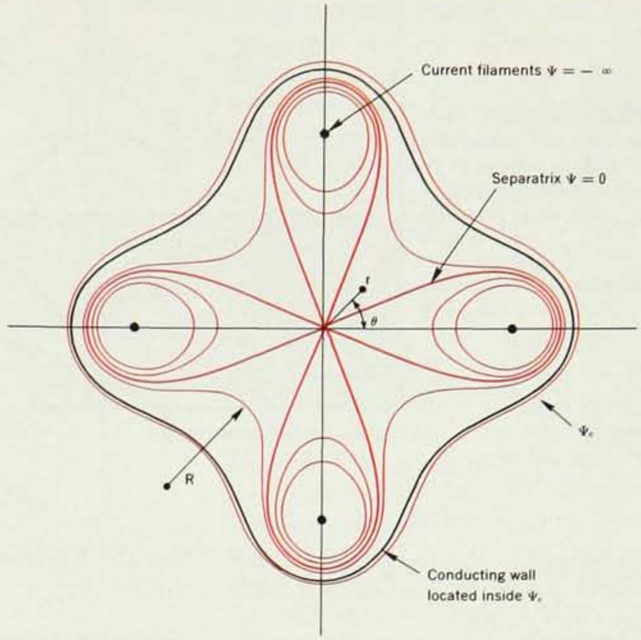
Tihiro Ohkawa is head of experimental physics in the thermonuclear research program at General Atomic. He took his PhD at Tokyo and in 1959 spent a year at CERN before joining General Atomic.



Norman Rostoker took his BASc and MA at Toronto and his PhD at the Carnegie Institute of Technology. He has recently left General Atomic to be chairman of the applied physics department at Cornell.



OCTOPOLE plasma confinement device. The four rods are seen inside the conducting outer wall. —FIG. 4



FIELD LINES of octopole. Their radius of curvature *R* is always positive inside the separatrix. —FIG. 5

where L is the distance and $V_A = B(4\pi nM)^{-1/2}$ is the Alfvén speed. This condition reduces to β equals $8\pi nMV^2B^{-2} < 2aRL^{-2}$ which provides an estimate of maximum plasma pressure that can be contained.

In 1961 a program was initiated at General Atomic by Donald Kerst and Tihiro Ohkawa to study first a linear and then a toroidal octopole. In 1962 Kerst started a similar program at the University of Wisconsin. The balance of this article will be devoted to discussing the results of the program at General Atomic.

Design of the octopole

The first experiments were conducted with a linear octopole to show that injection from a coaxial plasma gun is feasible.[7] Figure 7 is a time exposure of the plasma viewed from one end of the linear octopole. Then we made a toroidal machine that is illustrated in figures 1 and 2. The major diameter of the torus is 125 cm and the diagonal distance between centers of the conducting rings is 25 cm. The conducting rings are not in magnetic equilibrium and four 0.64-cm-diameter supports are required for each ring to withstand a peak force of 2000 kg per support. The octopole field is obtained by inducing current in the four rings which form the secondary of a transformer. The primary has 14 ten-turn windings which are connected through ignitrons to two 14-kV capacitor banks of 3600 μF each. Each set of ten primary turns has a crowbar ignitron across it, and the field is crowbarred at the peak of the first half cycle. The field rises in 400 μsec and then decays with a 2-msec time constant.

The coaxial gun shown at the left in figure 2 produces about 10^{18} particles with a mean energy of 100 eV. The plasma is guided through an expansion chamber which disposes of most of the neutral gas.

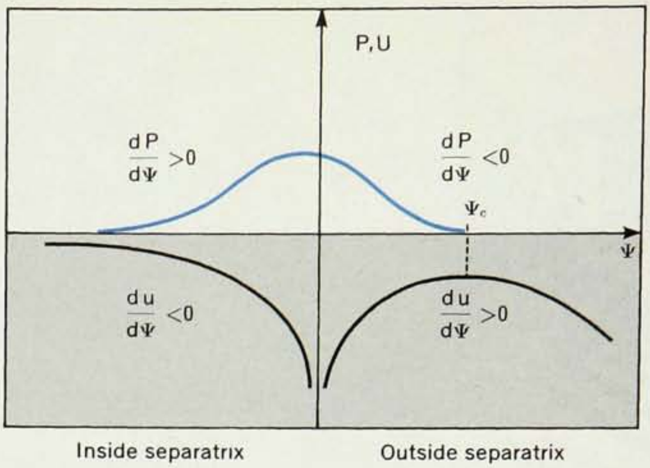
After injection plasma streams around the torus in both directions with a velocity of 10^7 cm/sec. A small part of the plasma is lost where the two streams meet at 180 deg from the injection port. In about 100 μsec the plasma settles down, and the density becomes uniform around the machine. Also during injection, there is a radial electric field in the plasma such that the potential drop is proportional to the ion energy; this decays to a very small value in about 100 μsec. Figure 8 shows the plasma density and the electron temperature on the multipole axis as a function of time measured by a Langmuir probe. The electron temperature is about 10 eV and constant during the experiment. The density is about 10^{12} cm^{-3} and decays with a 1-msec time constant after injection. The density profile perpendicular to the magnetic lines is shown in figure 9.

We measured ion energies by observing the charge-exchange neutrals that leave the plasma. The neutrals pass through a gas stripping cell and are then electrostatically analyzed. This measurement indicated that hot ions with 100 eV energy disappear in about 20 μsec. It has been shown that bombardment of walls during injection releases neutral gas near the injection port that subsequently removes the hot ions by charge exchange. This problem has been solved by technical improvements in the injection system and by reducing the plasma density (the neutral atom flux is proportional to the square of the plasma density) to 10^{11} cm^{-3} in which case the lifetime of 100-eV ions increased to 300 μsec.

Control of MHD instability

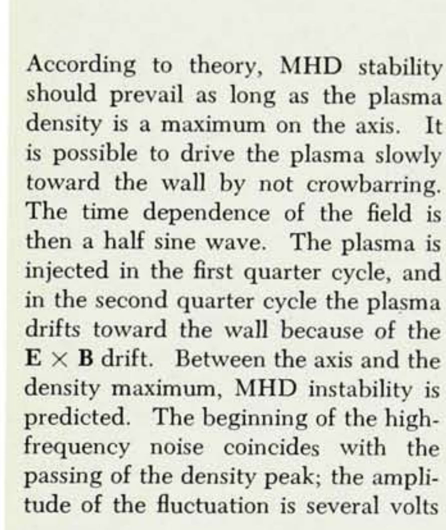
When the multipole field is crowbarred and the field decays with a 2 msec time constant, fluctuations in potential and density are observed to be quite small

$$e\langle\Delta\Phi\rangle/kT_e \lesssim \langle\Delta n\rangle/n \lesssim 1\%$$



PLASMA PRESSURE (color) and parameter U as functions of Ψ. U has the nature of a magnetic potential and forms a magnetic trap to contain the plasma. —FIG. 6

According to theory, MHD stability should prevail as long as the plasma density is a maximum on the axis. It is possible to drive the plasma slowly toward the wall by not crowbarring. The time dependence of the field is then a half sine wave. The plasma is injected in the first quarter cycle, and in the second quarter cycle the plasma drifts toward the wall because of the $\mathbf{E} \times \mathbf{B}$ drift. Between the axis and the density maximum, MHD instability is predicted. The beginning of the high-frequency noise coincides with the passing of the density peak; the amplitude of the fluctuation is several volts and the frequency ranges from 10 to 10 000 Hz.



TIME EXPOSURE of the plasma in a linear octopole built to test the injection method. —FIG. 7

Control of microinstability

When the multipole field is reduced, a weak instability appears that does not have the properties of any MHD instability. With a detailed experimental study of its properties we tried to see whether it can be identified with one of the many microinstabilities predicted by the linearized Vlasov equation. We made floating potential fluctuation measurements with electric double probes and measured the noise frequency and amplitude as functions of position, magnetic field, ion temperature and ion density.

The properties of the noise can be summarized as follows:

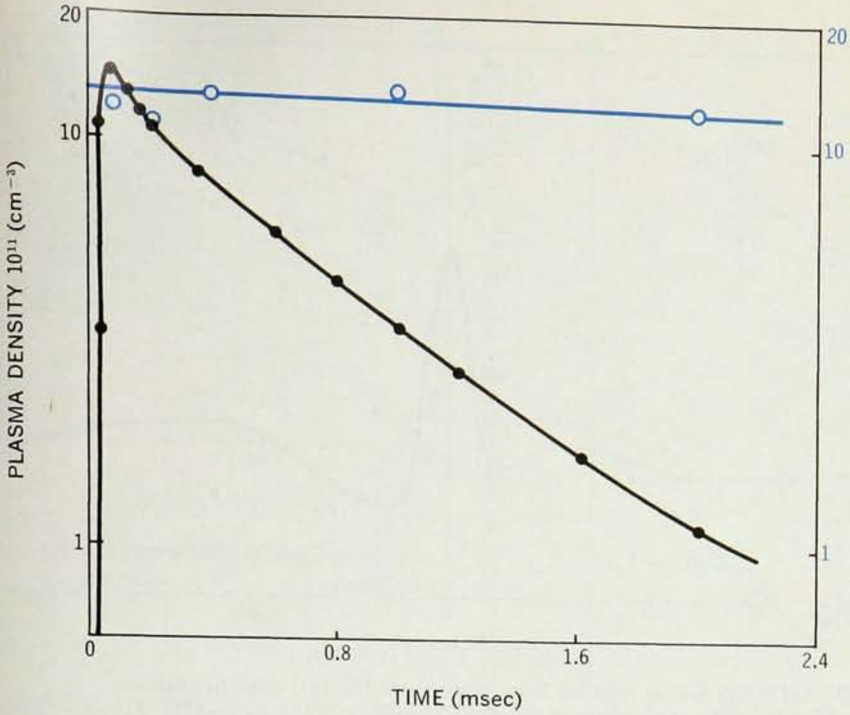
1. ω (frequency) $\propto B$ (field)
2. $k_\perp$ (wave number perpendicular to $\mathbf{B}$) $\propto B^2$; $k_\| \approx 0$
3. v_p (phase velocity) J_d (diamagnetic current) > 0
4. $\Delta n/n \propto -e\Delta\Phi$
5. Amplitude $A \propto B^{-2}$
6. Sensitive to ion temperature
7. A is small on the separatrix and largest when Δn is large
8. Absolute minimum B around the rod does not stabilize the mode
9. $d\omega/dk = \omega/k > 0$

Properties 2 and 4 rule out almost all modes predicted by linear theory except for the drift-cyclotron mode.[8] This is a microinstability that is predicted to occur at the cyclotron frequency whereas the observed frequency is about a factor of 5 less than the cyclotron frequency. However, previous calculations assume that the density changes little over an ion gyroradius and neglect the field-line curvature. Both approximations are inadequate for the present problem. Recent improvements[9] in the calculation have produced a satisfactory agreement between theory and experiment. The main feature of the improved calculation is the Doppler shifting due to drift motion resulting from the field-line curvature, that is, $\omega \approx \Omega_i - k_\perp g/\Omega_i$ where Ω_i is the cyclotron frequency, $k_\perp$ is the wave number and $g = V^2/R$ where V is the ion thermal speed and R is the radius of curvature of the field line.

Recently the effects of a small toroidal field have been studied. A toroidal field of about 120 gauss has been applied for a time long compared to the duration of the experiment. This study is of interest because we can look at small effects of certain features common to stellarators such as flux surfaces and magnetic shear. The small toroidal field has a substantial effect on the fluctuations as indicated in figures 10 and 11. The previously discussed mode disappears as a result of the toroidal field. The remaining noise is smaller in amplitude, more irregular and independent of background pressure. Thus we know that it does not depend on hot ions. We have also been able to reduce the amplitude of MHD fluctuations obtained when the plasma density maximum is off axis. This noise has been reduced by a factor of 10 with the application of a 60-gauss toroidal field.

Confinement of energetic ions

To avoid charge-exchange limitations we must work at densities less than 10^{11} cm^{-3}. The observation of energetic ions by means of gas stripping cells is not possible at such low densities. Instead we used the ion extractor tube developed by the Wisconsin group.[10] It is inserted at the edge of the plasma and the decay of ion flux through the tube is measured. Due to the ohmic decay of the current in the multipole rings the plasma should slowly drift toward the rings. The drift of course affects the ion flux at the outer edge where the extractor tube is inserted. To avoid this effect the multipole field was not crowbarred so that its dependence in time was a half sine wave. In the second quarter



VARIATION OF PLASMA DENSITY and electron temperature (color) with time. Electron temperature is roughly constant at 10 eV. Plasma density decays with time constant approximately 1 msec. —FIG. 8

cycle the plasma drifts away from the axis. Another capacitor bank was fired at various times in the second quarter cycle so that the decay of the magnetic field had a controlled delay. The ion signal had a corresponding delay. Thus the ion lifetimes could be determined by plotting the intensity of the ion signal against the time it appears (figure 12). We studied the effect of ring supports on the lifetime by putting in additional supports with the result shown in figure 13. These observations show that the observed ion decay times may be explained within a factor of two as the support loss.

Future prospects

The objective of the multipole experiment was to demonstrate MHD stability in a torus. This objective has been accomplished. Independent experiments at the University of Wisconsin have reached the same conclusions with respect to MHD instability.

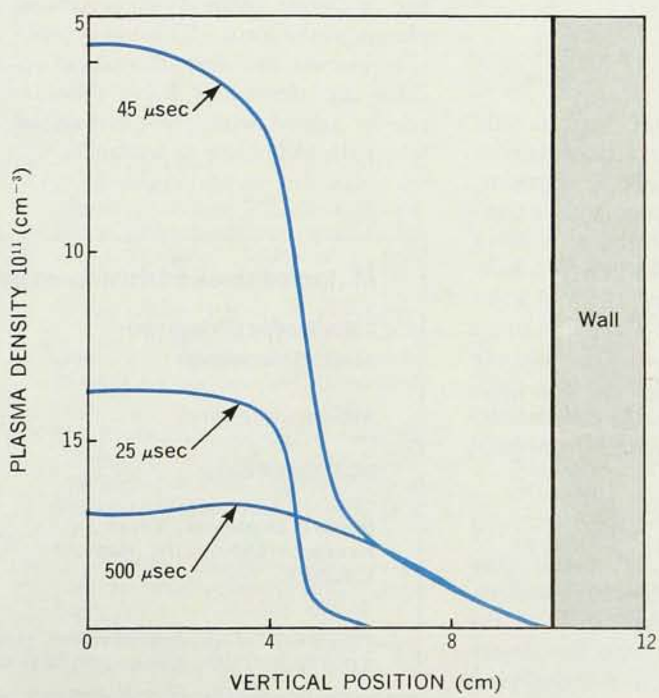
The important question for the problem of controlled thermonuclear fusion is whether or not pumpout (Bohm diffusion) can be avoided. The present results suggest that it can because the level of fluctuations is several orders of magnitude less than is observed with stellarators. A definite answer to the question would require the demonstration of a confinement time much longer than is predicted by Bohm diffusion. In this first generation of crude experiments the lifetime is limited by the support losses to a value that is ten times the Bohm diffusion time.

The development of a quiet plasma makes it possible to study specific modes of instability, make comparisons with theory and test methods of control suggested by theory. A specific example discussed here is the drift-cyclotron mode which is controlled by a small toroidal field.

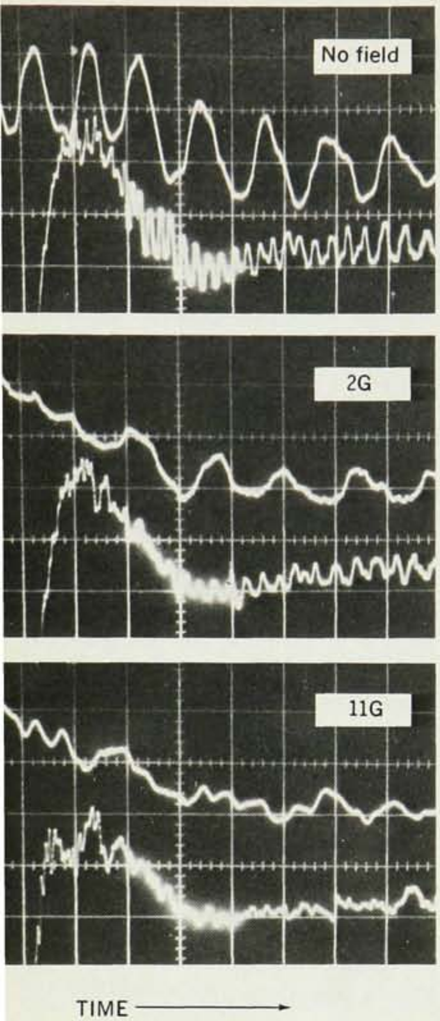
To obtain a long lifetime it is necessary to do something about the support losses; it is also necessary to prevent the ohmic decay of current in the rings. The following steps are under consideration:

A quadrupole has the advantage that the rings are in principle force-free. Thus a quadrupole can be designed with very small supports just sufficient to hold the rings against gravity when there is no magnetic field. Alternatively the rings could be allowed to drop and be caught as in the Levitron at the Livermore laboratory.

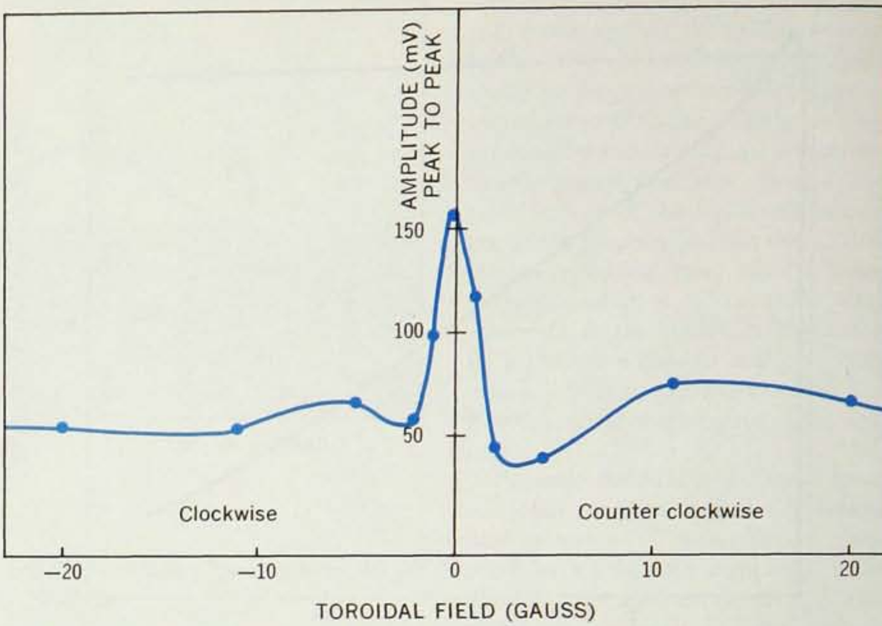
The ohmic decay of currents in the rods can be overcome by making the rods superconducting. A design of superconducting and levitated rods is being considered at Princeton's plasma laboratory. An alternative ap-



PROFILE of plasma density from the axis to the wall, 25, 45 and 500 μsec after injection.—FIG. 9



NOISE (8 cm from the axis) reduced by a toroidal field. —FIG. 10



NOISE AMPLITUDE is reduced from more than 150 mV peak-to-peak to about 50 mV by the application of the toroidal field. —FIG. 11

proach is to drive the rings directly with a constant voltage through conductors that also serve as supports. Some preliminary experiments at General Atomic show that dipole shielding of supports may be effective. (A hairpin coil of dimensions 10 by 2.5 cm was inserted into the plasma; with no current in the coil the plasma lifetime was reduced from 400 to 250 μsec; with 12 kA flowing in the coil the lifetime was restored to almost the original value.)

Further ahead

At present we are still mainly concerned with basic physical questions. The density and temperature of the plasma are quite far from the magnitudes necessary for a thermonuclear reactor. The technology for increasing the temperature is available; however this would require larger magnetic fields, plasma volume or both. The cost of experiments would be very much greater so that probably serious attempts to study kilovolt plasmas will not take place in the next generation of experiments. To increase the density without making charge exchange the dominant loss process, we must find a better method of producing plasma in the torus. This too is probably beyond the next generation because the question of Bohm diffusion can be settled with present densities where the technology is available.

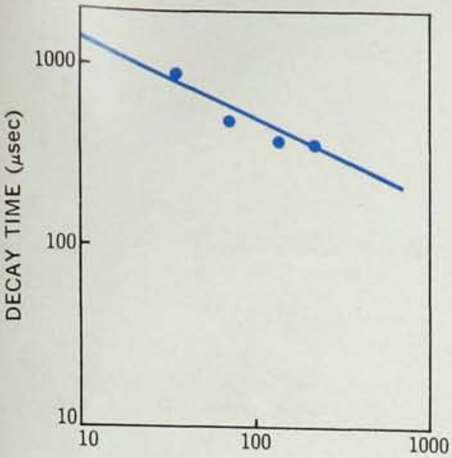
The ultimate objective of experiments such as the one described in this paper is fusion power. Although there is no rational way to predict when or whether this objective will be accomplished, a brief comparison of the present state of this experiment with other major experiments may provide some perspective. The major experiments in the United States[11] are listed in the table below.

In each case the experiment is limited either by technical or fundamental factors. Indeed the objective of each experiment is to apply the most advanced technology to a specific idea in order to determine the fundamental

Major controlled fusion experiments in the United States

C Stellarator (Princeton)	see text
ALICE (Livermore)[1]	neutral injection into an open-end magnetic trap
Astron (Livermore)[2]	injection of relativistic electrons that produce minimum-B confining fields
DCX (Oak Ridge)	injection of molecular ions into an open-end magnetic trap
Scylla (Los Alamos, Naval Research Laboratory, General Electric)	high-beta plasma produced by a linear pinch with plasma currents in the azimuthal direction

1 PHYSICS TODAY, November 1966, page 71
2 PHYSICS TODAY, August 1967, page 49



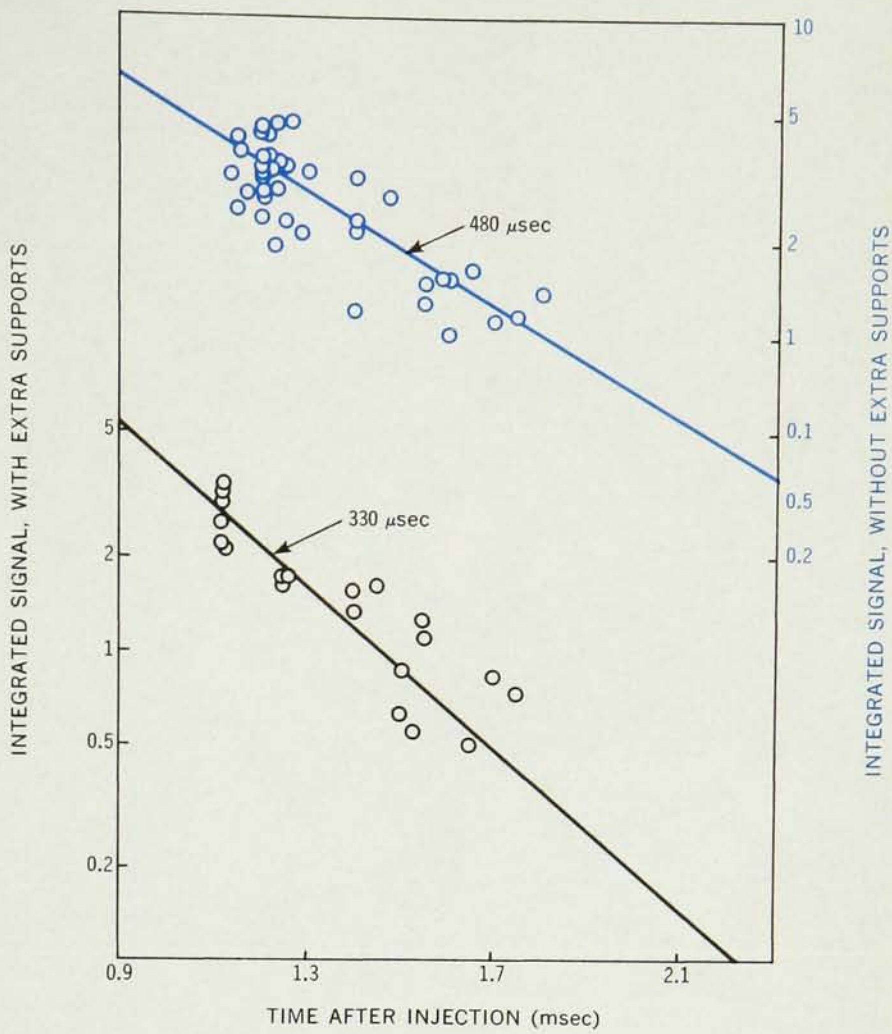
ION DECAY TIME as a function of ion energy. —FIG. 12

limitations. From this point of view the most advanced experiments are the C Stellarator, DCX, and ALICE. In each of these experiments confinement seems to be limited by instability of the plasma. Confinement in Scylla is not determined by instability but by the short length of the device so that the plasma streams out in a few microseconds. Astron has thus far been developed until about 5% of the required electron current is available. No significant instability has been observed yet; so the limitations are in the technology. The present multipole experiments are at a similar stage in that plasma confinement is not limited by instability.

In the experiments that have reached fundamental limitations, the plasma is of no practical consequence for fusion. The purpose of the experiment is to understand the fundamental limitation and see if it can be removed. On the basis of present knowledge it is expected that when Scylla, Astron or multipole experiments reach their fundamental limitations, the plasma will be of some practical significance. We can not predict the time scale for this development because the fundamental limitations are not known. Indeed if they were known the experiments would be unnecessary.

* * *

This work was carried out under a joint General Atomic–Texas Atomic Energy Research Foundation program on controlled thermonuclear reactions.



EFFECT OF RING SUPPORTS on the ion lifetime. Signal with extra supports is shown in black; compare with the signal obtained without extra supports, shown in color. —FIG. 13

References

1. W. Stodiek, D. J. Grove, J. O. Kessler, *Proceedings of the Second IAEA Conference on Plasma Physics and Controlled Thermonuclear Fusion Research* (Culham 1965) vol. 2, page 687, IAEA, Vienna (1966).
2. L. A. Artsimovich, V. V. Afrosimov, I. P. Gladkovsky, op. cit. ref. 1, vol. 2, page 595; (see also the summary by L. Spitzer, op. cit. ref. 1, vol. 1, page 3).
3. D. Eckhartt, G. von Gierke, G. Grieger, op. cit. ref. 1, vol. 2, 719 (1966); Princeton Conference on Toroidal Confinement, 11–15 July, 1966.
4. D. J. Grove, Princeton Conference on Toroidal Confinement, 11–15 July, 1966.
5. S. I. Braginskii, B. B. Kadomtsev, Plasma Physics and the Problem of Controlled Thermonuclear Reactions, vol. 3, page 356, Pergamon Press, New York (1961).
6. M. N. Rosenbluth, C. L. Longmire, Ann. Phys. **1**, 120 (1951).
7. T. Ohkawa, A. A. Schupp, H. G. Voorhies, W. C. Duesterhoeft Jr, Phys. Fluids **6**, 1526 (1963).
8. A. B. Mikhailovskii, Nucl. Fusion **5**, 125 (1965); N. A. Krall, M. N. Rosenbluth, Phys. Fluids **8**, 1488 (1965).
9. N. A. Krall, T. K. Fowler, Phys. Fluids **10**, 1526 (1967); D. Bhadra, Phys. Rev. **161**, 126 (1967); T. Ohkawa, M. Yoshikawa, Phys. Rev. Letters **17**, 685 (1966).
10. R. A. Dory, D. W. Kerst, D. M. Meade, W. E. Wilson, C. W. Erickson, Phys. Fluids **9**, 997 (1966).
11. T. K. Fowler, R. F. Post, Scientific American **215**, No. 6, page 21 (1966). □