Recent developments in

CONTROLLED FUSION

By A. S. Bishop

This review of work under Project Sherwood, with emphasis on the Princeton stellarator program, is based on invited papers presented at the Northeastern Conference of the Institute of Electrical and Electronic Engineers on November 4, 1963, and at a meeting of the American Nuclear Society on January 6, 1964. Dr. Bishop is a physicist on the research staff of the Princeton University Plasma Physics Laboratory.

The basic problems of controlled fusion are well known. Briefly they are the following: first, with deuterium or a deuterium-tritium mixture, to produce a pure low-density plasma of exceedingly high temperature (several hundred million degrees Kelvin—i.e., several tens of thousands of electron volts); second, to confine this plasma adequately and stably by means of an appropriate magnetic field configuration for a sufficiently long time that an appreciable fraction of the nuclei can undergo fusion; and finally, to capture the energy released and harness it for useful purposes.

Of these formidable problems, the most critical is summarized by the words "adequate and stable confinement". It is now all too clear that there are a whole host of instabilities which are poised, ready to strike and cripple any attempt to produce a hot plasma with even the most ingenious methods of confinement. Many types of these instabilities have been predicted theoretically (among them, the various hydromagnetic instabilities and, more recently, the so-called universal instabilities), and a number have already been observed experimentally. Some of them have rapid rates of growth and would clearly be lethal if permitted to develop; others grow rather slowly and may prove relatively innocuous. The important point is that, thanks to the theoreticians, we are slowly becoming more sophisticated in the mathematical description of these instabilities and, accordingly, are gaining much better insight into their behavior. One example, which will come up later in our discussion, involves the recent incorporation into the theory of *finite* Larmor orbits for ions and electrons (rather than considering them to be negligibly small). It turns out that the incorporation of this quantity tends, in general, to provide a stabilizing effect upon the predicted behavior of the plasma. Another example is the recent trend—accelerated by the encouraging results of the Soviet physicist, Joffe—to modify the configurations of magnetic confinement so that the plasma finds itself in a region of minimum potential. In such "minimum-B" configurations, the strength of the magnetic field in the confinement region increases everywhere with increasing distance from the plasma.

A quantity of particular interest in the controlled fusion field is the product $N\tau$ where N is the density of the plasma, and τ is the confinement time. It may be shown that, if a system is to be of thermonuclear interest, the product $(N\tau)$ must be of the order of 10^{15} sec/cc. An associated critical factor is the ion temperature, which must be of the order of 10^4 to 10^5 electron volts. The goal of the fusion program is thus seen to be in the upper right-hand corner of Fig. 1.

For the past twelve years there has been a rather intensive program of research and development in the United States directed toward this specific goal. The various approaches which have been pursued can, in general, be divided into two categories. In one group (A) one starts with an essentially cold gas of moderate density (10^{13} to 10^{16} atoms/cc, say), ionizes it to form a low-

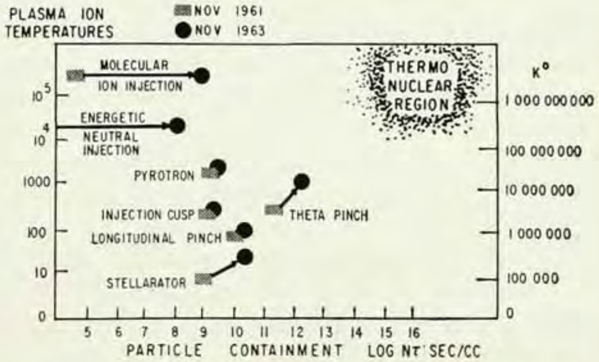


Fig. 1. A comparison of the status of each of the approaches discussed here, with a crude indication of the extent of progress made in the last two years.

temperature plasma and then heats this plasma by one means or another to thermonuclear temperature within a confined region.

In the second group (B), one starts with a beam of particles which already have energy sufficiently high to permit fusion to occur. Then by ingenious methods of injection and trapping into a suitable confining field, one attempts to build up the density to values of thermonuclear interest, while simultaneously converting the directed particle velocities into the required random motion of a hot plasma.

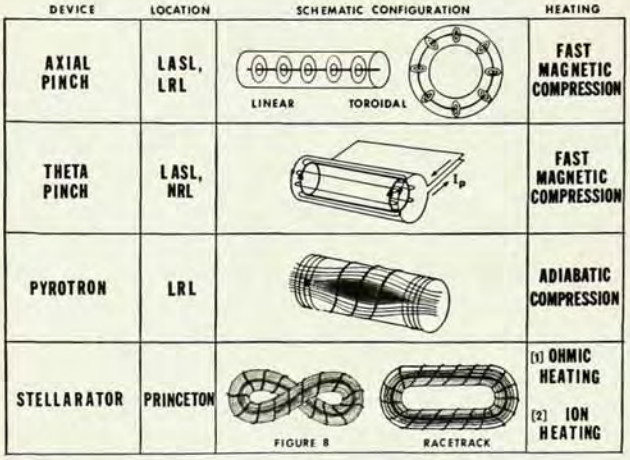


Fig. 2. Schematic diagram of four approaches to controlled fusion involving low-energy injection, with subsequent heating. (Note: LASL = Los Alamos Scientific Laboratory; LRL = Lawrence Radiation Laboratory, Berkeley and Livermore; NRL = Naval Research Laboratory; ORNL = Oak Ridge National Laboratory.)

Longitudinal pinch

Figure 2 illustrates, in highly schematic form, the basic configurations of those low-energy injection schemes which are under investigation in the US Sherwood program. The first among these is the longitudinal-pinch approach, which has been developed primarily at Los Alamos Scientific Laboratory in New Mexico, and the Lawrence Radiation Laboratories in Livermore and Berkeley, California. In this concept, a large axial current is induced to flow in the discharge chamber (either straight or toroidal in shape), and the interaction of this current with its own encircling magnetic field results in the constriction of the discharge to a fine filament of current at the center of the tube. Sizeable heating of the plasma occurs by fast magnetic compression during the constriction process. While the pinch concept was historically the first Sherwood concept to be developed, it was also the first to run into serious difficulties—namely, the onset of a kink instability which grows very rapidly in time, driving the plasma into the surrounding walls of the vessel within a time interval of the order of several microseconds.

A sizeable program has continued to try to overcome this difficulty by a variety of ingenious methods, most of which have proven to be unsuitable for one reason or another. Probably the most interesting work in this approach at present involves the so-called "Hardcore pinch", involving a solid conductor within the center of the tube, so that the discharge is confined to the annular region surrounding the conductor. Such a configuration has been shown to be theoretically stable for an infinitely conducting plasma. In practice, however, instabilities continue to disrupt the plasma confinement, presumably because the conductivity is not sufficiently high.

Theta pinch

A much more promising pinch approach (at least for the moment) is the so-called theta pinch, which is being very actively pursued at several sites—particularly at Los Alamos and at the Naval Research Laboratory in Washington, D. C. Here the configuration is essentially orthogonal to that of the longitudinal pinch. Passage of a sudden high current through a single-turn loop induces an equal and opposite current to flow in the discharge chamber, thus creating a longitudinal magnetic field in the intermediate annular region. Heating again results from fast compression of the plasma by the magnetic field.

In devices of this type, it is primarily the *ions* which are heated. In the work at Los Alamos, for example, the electrons are heated to about 400 eV; ion temperatures, however, of 1800 eV have been achieved, with plasma densities of 10^{17}/cc. As is typical of these devices, rather copious quantities of neutrons are emitted—about 10^8 per pulse.

It must be stressed that these devices have, in the past, usually been plagued with instabilities, and the discharge usually lasts only of the order of 5 microseconds. Recently, however, significantly larger theta pinches have been built which show much less evidence of macroscopic instabilities. One which has recently come into operation at Los Alamos involves magnetic fields of more than 100 kG, and the losses are reportedly consistent with particles diffusing out the ends (there are no mirrors). The present plan is to add mirrors, and also an enormous supplementary capacitor bank to sustain the magnetic confining field for 50 microseconds.

Compression mirror machine (Pyrotron)

The third approach to low-energy injection is the compression mirror machine, developed at Livermore. Here, in contrast to the pinch concept, confinement is achieved by means of *externally* applied magnetic fields. A relatively low-energy plasma is injected into the straight discharge chamber at a time when the confining field is low. The field is then increased in magnitude at a reasonably slow rate (i. e., milliseconds, instead of microseconds), thereby trapping the particles between the magnetic mirrors and heating them by adiabatic compression. The compression is sometimes carried out in two or more successive stages, the hot plasma from one stage being transferred to an adjacent smaller device for further compression and heating.

One such multistage device produces plasma of 4-keV energy, with densities of 10^{13} particles/cc. As of a year or so ago, the heated plasma as a whole underwent a slow transverse drift to the walls because of small magnetic asymmetries. These asymmetries have been corrected, so that the plasma now stays reasonably well centered in the vessel. The neutrons which are produced arise from interaction within the plasma itself, rather than at the walls. Nevertheless, the reaction rate starts dropping off after about 150 microseconds. While hydromagnetic instabilities may also be involved, it is currently believed that charge-exchange processes are primarily responsible for this drop-off. A larger multistage device is now under construction, with confinement volume between two and three times the earlier size.

Using a separate one-stage mirror machine, it has been demonstrated that an instability may be produced or suppressed at will, by appropriate choice of parameters for the plasma discharge. Moreover, the regions of stable and unstable operation appear to conform well with recent theoretical predictions, which take into account the stabilizing effect of the finite Larmor orbits. It has also recently been determined that if the magnetic field configuration is modified to produce a "minimum-B" field, the previously-found regions of instability are transformed into regions of stable operation.

The last approach in this group, being carried out at Princeton University, employs the stellarator concept which uses an endless tube with an externally imposed magnetic field for confinement. We defer discussion of this concept until later, however, and turn instead to the second group which involves the injection of *high*-energy particles.

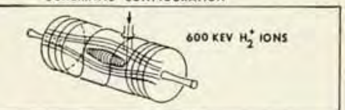
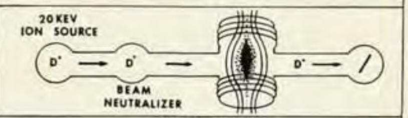
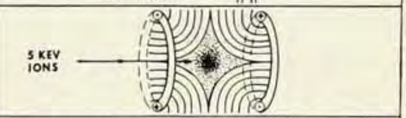
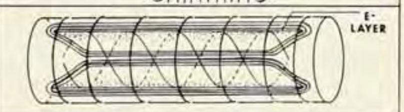
DEVICE	LOCATION	SCHEMATIC CONFIGURATION
MOLECULAR ION INJECTION	ORNL	
ENERGETIC NEUTRAL INJECTION	LRL	
INJECTION INTO CUSPS	LASL	
ASTRON	LRL	

Fig. 3. Schematic diagram of four approaches to controlled fusion involving injection and trapping of a beam of high-energy particles, with subsequent conversion of the directed particle velocities into the required motion of a hot plasma.

Molecular ion injection

Figure 3 illustrates the high-energy injection schemes which are under investigation. The first approach, being pursued at Oak Ridge National Laboratory, injects 600-keV molecular hydrogen ions into a magnetic-mirror geometry. The molecular ions dissociate by one of two processes: they collide with neutrals and other trapped particles or, from an excited state, they are dissociated by the Lorentz force exerted by the magnetic field. If desired, the rate of dissociation can be enhanced by the addition of a lithium arc, flowing along the lines of force near the axis, with which the molecular ions interact. In this work it is essential not only to inject an intense beam of molecular ions but also to produce an exceedingly low background pressure of neutral gas, so as to minimize losses by charge exchange—thereby increasing the confinement time and permitting the density of energetic trapped ions to build up as rapidly as possible. Appreciable progress has been made over the last few years, with improvements of several orders of magnitude in the confinement time of individual particles. Furthermore, a new and larger device has just recently come into operation; it has ion-beam intensities some seven to eight times greater than that of the first machine and a much greater probability for dissociation of the incident beam.

In both devices, however, there is evidence of what is called a "clustering instability", which appears to develop and to cause energy dispersion of the plasma. The net result of this and other effects has been to prevent the build-up of density in the smaller model to beyond about 10^8 particles/cc. In the larger model, use of a lithium arc in the dissociation process has permitted an increase in density to values of about 10^{10}/cc. The nature of the above instability is not clearly understood and is being studied intensively. There is, however, very recent evidence that the stability may be improved somewhat by providing supplementary heating to the electrons within the trapped plasma.

Energetic neutral injection

Instead of molecular ions, an alternative procedure is to inject a beam of energetic neutral particles, again employing a magnetic-mirror configuration for confinement. This approach, being pursued at Livermore, involves the production of a beam of 20 keV excited neutral atoms which then freely enter the discharge chamber, where they are ionized either by the Lorentz force in the magnetic field there, or by collisions with residual background gas. The result, again, is the build-up of a plasma of high mean kinetic energy (20 keV in this case). To date, only relatively modest plasma densities have been achieved—of the order of 5×10^8 ions/cc. Here it is not clear exactly whether the build-up in density is being limited by charge-exchange processes or some other mechanism.

Despite the low density, interesting and unusual cooperative effects have been observed. These appear to be low-frequency *stable* modes of oscillation of a high-temperature plasma. Such stable oscillations are predicted by recent extensions of the theory of finite orbit stabilization.

Very recently, modification of the magnetic confining field to a "minimum-B" configuration has begun, in the hope of improving the confinement time of the trapped particles.

Injection into cusps and Astron

For the sake of completeness, Fig. 3 shows two other important approaches which should be mentioned—namely, injection into cusps, and Astron. Because of space limitations, however, I will not go into any details concerning them. Suffice it to say that the work on high-energy injection into cusps is not well understood at present. While the beauty of the cusp-configuration is that it is theoretically completely stable against interchange instabilities, it is found in practice that the particles leak out. The basic reason for this loss is believed to be the presence of a nonadiabatic null-point at the center of the cusps, which essentially scatters particles into paths which permit them to escape out along the central plane. The configuration is being altered somewhat to avoid this difficulty—thereby hopefully halting the loss of such particles.

Last but not least, a word concerning the Astron concept: This approach involves the creation of a closed magnetic configuration by the combination of an externally-imposed axial magnetic field and an opposing magnetic field produced by a layer of relativistic electrons. These electrons are injected from the outside and trapped into an annular layer (the so-called E-layer). Since the construction of this ingenious but complicated device is not quite complete, I will limit my comments to wishing it success when it comes into operation during the coming year.

Present state of progress

Here, then, are the major approaches which are being pursued in the US fusion program. One might well ask where they stand with respect to each other and with respect to the ultimate goal. Figure 1 provides some insight into this question.

Using the N_T vs E_i presentation discussed earlier, the graph shows the status of each of the approaches—both as of November 1961 and as of November 1963. The length of the arrows gives a very crude indication of the extent of the progress in each of them over the past two-year period. It must be stressed, however, that progress in this field occurs usually in a sequence of spurts, often interspersed with lengthy intervals of seemingly little advance, spent in consolidation of the data and construction of new equipment.

I think it is interesting to note that, of the various approaches which have been seriously investigated, none has yet fallen by the wayside. Indeed, so capricious are the winds of progress in this embryonic field that it is difficult to know which approach, if any, is likely to be the first to reach the thermonuclear region of interest.

Let us turn now, however, to a more detailed consideration of the approach which is presently lowest on the N_T totem pole—the stellarator concept.

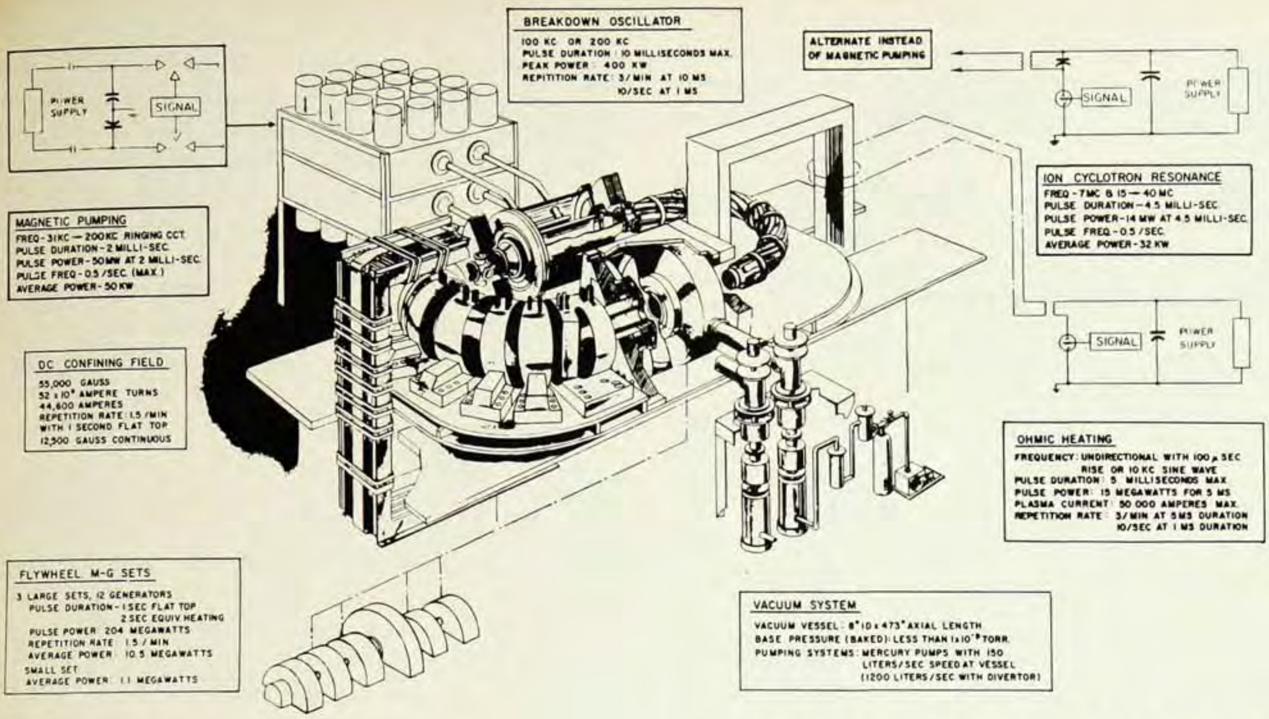


Fig. 4. Schematic view of the Model-C Stellarator, giving the characteristics of the major components.

The Stellarator

At Princeton, the stellarator concept of Lyman Spitzer has been investigated with a series of experimental models of increasing size and complexity, culminating in the so-called Model C Stellarator, which was brought into preliminary operation about two and a half years ago.

The discharge tube itself, eight inches in diameter, is shown in Fig. 4. Surrounding the tube are the large coils which provide the magnetic confining field strengths of up to fifty kG. It should be noted that while a full-scale Stellarator is envisioned as a continuous (rather than pulsed) operation, in all of the smaller devices—Model C included—operation is carried out on a pulsed basis in order to keep power costs within a reasonable figure. In normal operation, the magnetic field is brought up to its desired value (20-50 kG) once every thirty seconds for a period of about one second, during which time all of the plasma ionization and heating takes place.

Power for the field is provided by a set of three huge motor generator sets (Fig. 5), each with an associated flywheel of 96 tons from which the energy is drawn during the pulse. Even under pulsed operation, the power consumption is sizable (as much as 200 MW during each pulse, amounting to 12 MW average).

An important requirement of the stellarator concept is that there be a rotation of the magnetic lines of force, in order that the plasma will stay in an equilibrium position in the center of the discharge tube. In most of the smaller stellarator models, this so-called rotational transform was achieved by twisting the tube into a figure-eight configuration; the Model-C Stellarator, however, has a race-track configuration, with equilibrium being achieved by the addition of helical windings in each of the U-bends. Actually, the two helical

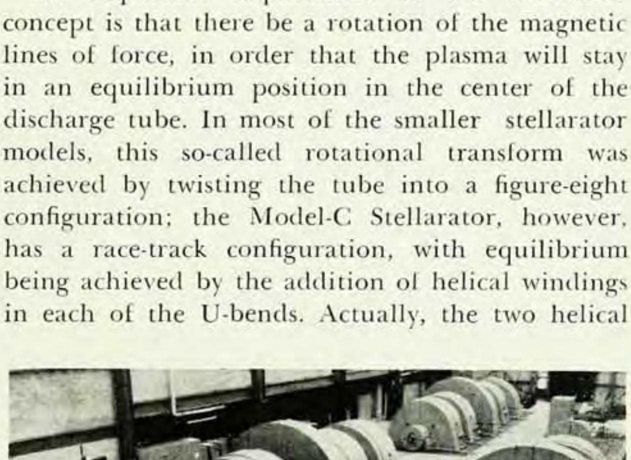


Fig. 5. The three large motor-generator sets (each with flywheel) used to power magnetic field of the C Stellarator.

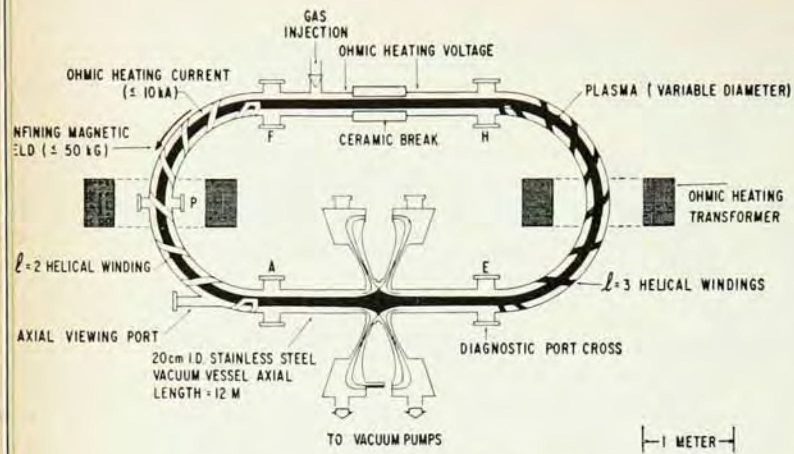


Fig. 6. A schematic drawing showing the basic plan of the Model-C Stellarator (as of November 1963), as viewed from above.

windings are somewhat different and they serve two purposes: not only do they provide equilibrium, but they also provide a certain degree of stabilization against magnetohydrodynamic instabilities.

Figure 6 gives a plan view of the C Stellarator, showing the major components as they now exist. One component which has only recently been added is the divertor, which plays an exceedingly important role in the reduction of impurities. The divertor consists of a set of coils which take the outermost lines of magnetic flux and divert them into a separate chamber. Energetic plasma particles which, in their circuits around the Stellarator, slowly diffuse outward across the magnetic lines of force, will no longer be able to strike the vessel wall and release impurities which would tend to cool the discharge. Instead, particles in the outer shell of the plasma are now peeled off and transported to the separate chamber where they are neutralized and pumped away. An over-all view of the C Stellarator is shown in Fig. 7.

The first and only method of heating which has been incorporated to date in Model C is that used in the smaller B-size models: ohmic heating produced by inducing, via the transformer cores shown in Fig. 8, a relatively small unidirectional current to flow axially in the plasma. This method, which heats primarily the electrons, is suitable for achieving temperatures of about 500 000°K (50 eV), but not much beyond. Experiments up to the present time have been devoted to an intensive study of plasma behavior at these low temperatures with emphasis placed on two major prob-

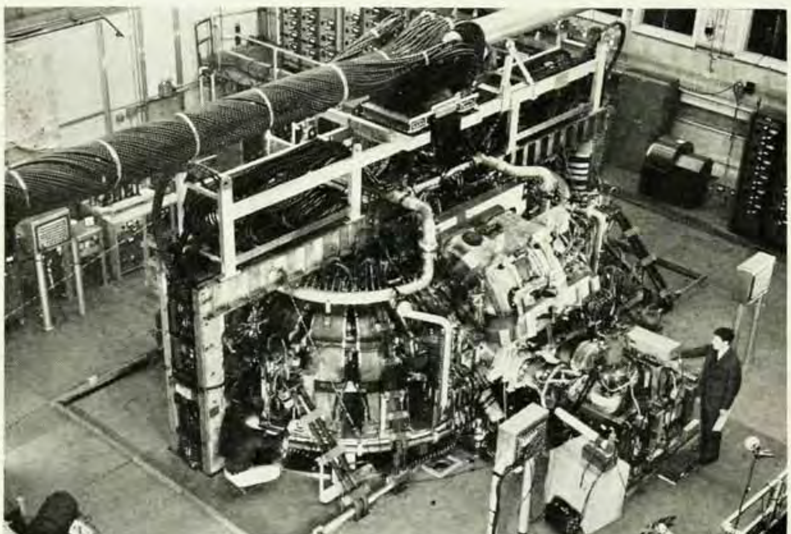


Fig. 7. An over-all photographic view of the Model-C Stellarator showing transformer for ohmic heating, magnetic field coils, and vacuum system.

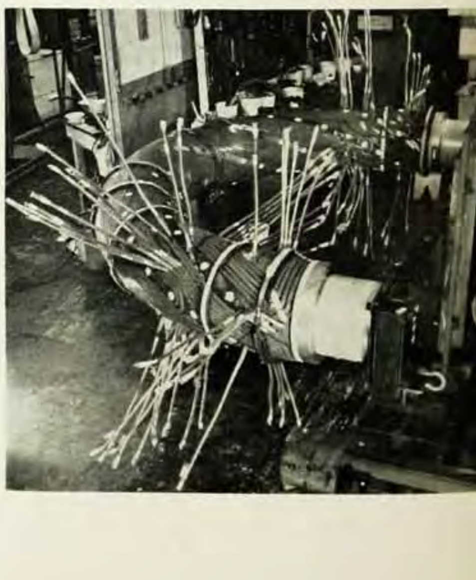


Fig. 8. Photograph of the SF-3A helical windings, prior to their installation in one of the U bends of the C Stellarator.

lems: (a) impurity radiation; (b) particle loss to the walls ("pumpout").

With regard to the first, since even minute quantities of impurities in the discharge can result in severe radiation losses, it is essential to determine the type of impurities present, whence they come, and how to reduce their level. Measurements with a calibrated ultraviolet monochromator have shown that, in contrast to results obtained with earlier models, the only impurity of any significance found in the C-Stellarator is that of oxygen. Rather curiously, the oxygen appears to be released in a burst from the vessel walls in the early part of each discharge, and in hydrogen discharges of last fall—prior to the addition of the divertor—nearly all of the radiation emitted was due to the oxygen impurities. Recent experiments with the divertor in operation now show that the concentration of oxygen impurity has been reduced by a factor of about fifty (from about 3% to less than 0.08% of the hydrogen population), and that, correspondingly, the oxygen radiation is now totally negligible compared with the hydrogen radiation. The impurity problem has thus been solved—at least for the moment.

On the question of plasma confinement, the stellarator program has long been plagued by an anomalously high rate of plasma loss, known as "pumpout". Specifically, the plasma escapes to the walls at a rate which is several orders of magnitude greater than that which would be expected on the basis of classical diffusion theory. Despite intensive experimental and theoretical work, the pumpout phenomenon is still with us and is still not really understood. Recent experiments lend credence to the belief that there are at least two separate but overlapping causes of pumpout—the finger of suspicion being pointed specifically at inadequate equilibrium when low heating currents are used, and at universal instabilities for the case of higher currents. Once the cause of pumpout is adequately understood, it is likely that steps can be taken to prevent its occurrence.

On the more positive side, it has been rewarding to find that the particle confinement time in the C Stellarator is of the order of several milliseconds —a value which is about ten times greater than that typical of the smaller B-size stellarators. The energy replacement time, (defined as the time in which the energy input into the plasma equals the total kinetic energy of the electrons) has likewise improved more than an order of magnitude and now has a value of about 500 microseconds.

These results are sufficiently encouraging that, despite the continuing presence of pumpout, it is deemed desirable to move into the next phase of the stellarator program—i.e., the incorporation of ion-heating into the C Stellarator during the first part of 1964.

Of the two alternative methods for which equipment has been assembled, the first to be installed will be the ion cyclotron-resonance method. This approach has already been tested out, with moderate success, in a smaller experimental device consisting simply of a straight section of tube with magnetic mirrors at each end. Waves are produced by an induction coil located at the center of the mirror system and powered by an rf generator capable of delivering one MW of pulsed power at about 16 megacycles. It has been shown that the induction coil is very effective in coupling large amounts of power (300-400 kW) from the rf supply into waves which propagate in the plasma away from the coil. When these waves propagate into a region of slowly-decreasing magnetic field (a so-called magnetic beach), strong absorption takes place in the vicinity of the point where the wave frequency equals the local ion cyclotron frequency. Thus, most of the plasma heating takes place at the beach.

Temperature measurements (using a diamagnetic loop) indicate an average temperature of the ions and electrons to be about 200 eV. Since the electron temperature is measured separately (by Langmuir probe and spectroscopic methods) to be only about 10 eV, we can conclude that most of the plasma energy is in the ions. This conclusion is verified by the energy spectrum of the ions scattered out the ends of the device, as measured with a magnetic ion-energy analyzer.

Now, the energy-loss time is found to be 20-50 microseconds; the particle loss time, on the other hand, is of the order of 200 microseconds. This anomalous behavior apparently results from the rather high influx of impurities during the heating pulse itself in this device. Thus, we believe this experiment to be essentially radiation-limited: hot ions transmit their energy to relatively cold electrons, which in turn give up their energy to the ionization and excitation of impurity atoms which then radiate furiously. (For densities of 3×10^{13}/cc and electron temperatures of 10 eV, the equipartition time is $\sim$50 microseconds. The rate of energy loss by this process would be expected to be about 200 kW, approximately that at which energy is supplied to the plasma from the ion cyclotron waves.)

In the application of ion cyclotron-resonance heating to the C Stellarator early this year, 6 MW of rf power will be applied for 5 milliseconds, with a repetition rate of once per 30 seconds.

Extrapolation from results with the smaller model leads us to hope that, even in the face of pumpout, temperatures in excess of 1000 eV may be achievable. This expectation has been recently strengthened by the encouraging results regarding the low level of impurity in the C Stellarator.

While the rapid heating obtainable by this method appears to be essential during the present era of "pumpout", we are not blind to some of the possible shortcomings of this mechanism. Among other things, the amplitude of coherent ion motion is considerable, and it is therefore possible that the ion cyclotron mechanism of heating may enhance the development of instabilities. In any case, we are not putting all of our eggs into the ion cyclotron basket. In the hope and expectation that our present pumpout difficulties will soon be understood and overcome, equipment is being assembled and tested for an alternative method of ion heating—"magnetic pumping", which is appreciably slower but is likely to be more suitable for large devices.

The principle of magnetic pumping, as applied to the C Stellarator, is as follows: In one of the straight sections of the race-track configuration, a piece of the stainless-steel vacuum vessel is removed and replaced with a piece of ceramic tubing having a diameter roughly twice that of the vessel itself. The value of the confining field in this section is reduced from its previous value of, say, fifty thousand gauss to about ten thousand gauss. Surrounding the ceramic tube is a coil fed by high-power radio-frequency systems which serve to increase and decrease the magnetic field in this region with about a 50% modulation (i.e., 5-15 kG). Thus the plasma in this section is alternately compressed

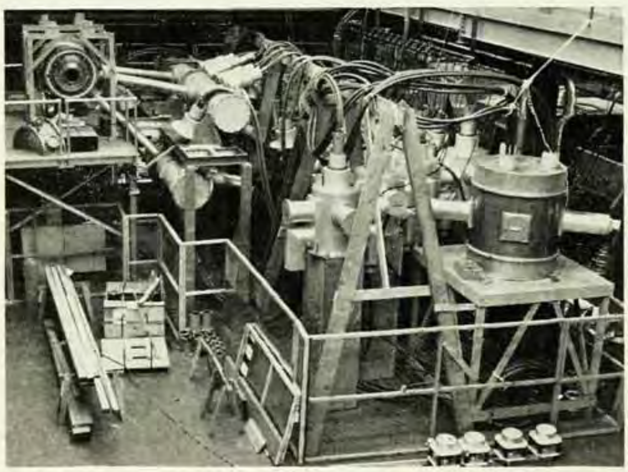


Fig. 9. A photograph of the equipment which has been assembled for magnetic pumping. The ceramic section through which the plasma would pass is seen on the platform at the left.

and expanded at radio frequency, resulting in successively heating and cooling the plasma. Now, if the frequency of these oscillations is properly chosen, the process will be thermodynamically not completely reversible; the temperature of the plasma will thereby increase, since more work will be done on the system during the compression phase than will be removed during the subsequent expansion phase. For optimum heating in the stellarator, the half-period of oscillation should be chosen to be comparable with the transit times of ions passing through the region over which the field is applied.

In these circumstances, the ions suffer essentially no collisions in traversing the magnetic pumping region, but they gain transverse energy due to radial compression by the oscillating field. In making their way around the rest of the tube, however, the ions will have time to undergo collisions and thereby transfer some of the transverse energy into motion parallel to the magnetic field.

To provide the necessary reactive power (current and voltage in the 100 kA, 100 kV range) it is most economical to use a high Q circuit, the oscillations of which are maintained by high-power vacuum tubes. Since the Q attainable for coils, cables, and spark-gaps is in the neighborhood of 500, capacitors with a Q of this same order are desired. These have been developed after several years' effort.

In the application to the Model-C Stellarator, present plans call for 80 MW of rf power, to be supplied by eight tubes and eighteen large capacitors (with a capacitance of $\frac{1}{2}$ μF apiece). The average power consumption will be about 10 kW. If and when pumpout can be overcome, this equipment should be capable of heating the plasma to nearly one hundred million degrees. Figure 9 shows a picture of the equipment assembled for this purpose. The ceramic section through which the plasma passes is dwarfed by the equipment surrounding it—capacitors, sparkgaps, tubes, resonant "match-boxes", etc.

I hope that I have been able to give you an indication of the present state of the fusion program in general and of the stellarator program in particular. Even more important, I have tried to indicate that, while there has been no major break-through and none is expected, there has been appreciable progress forward on most fronts, and there is an atmosphere of suppressed anticipation permeating the entire fusion effort.

The next several years will be exceedingly interesting—and possibly critical—years in the development of the program.