

Experiments on the Ohmic Heating and Confinement of Plasma in a Stellarator

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In 1951 Spitzer proposed the stellarator as a device for confining plasma and heating it to thermonuclear temperatures.¹ Since that time, a series of devices has been constructed and operated at Princeton University for experimental research in such systems. This paper summarizes experimental results in the fundamental areas of heating and confinement. Accompanying papers present evidence for the importance of cooperative processes in the plasmas of these devices.^{2, 3}

STELLARATOR PRINCIPLES

Confinement

Confinement of plasma in a stellarator is provided solely by externally produced magnetic fields. As described in detail elsewhere, the magnetic configuration is that of a torus with rotational transform.^{4, 5} This geometry gives plasma confinement of a higher order than that given by a simple toroidal field. It does so by virtue of providing a path, *along* magnetic lines of force, by which currents may easily flow to neutralize charge accumulations produced by particle drifts in the general toroidal field. Two methods have been used to give rotational transform to the Princeton devices. The first, illustrated in Fig. 1, distorts the torus into the form of a "figure eight", while the second employs currents in auxiliary helical conductors on the surface of a regular toroidal tube. In both cases the general "axial" field is provided by current flowing in copper coils surrounding the tubes. In this and in the accompanying papers,^{2, 3} the results presented were obtained on equipment employing the figure-eight geometry only.

Even with the rotational transform, plasma confinement will not be perfect. Collisions between unlike particles in the plasma will always give rise to a diffusion across lines of force. In a quiescent plasma in which cooperative oscillations are negligible, this classical collision diffusion will be the dominant process. If instabilities and other cooperative phenomena are present, particles may reach the wall even more rapidly than in a quiescent plasma.

Following Spitzer⁶ it can be shown that, assuming

classical collision diffusion, the mean confinement time, τ_c , for helium is given by

$$\tau_c \sim (20B^2T^{3/2}R^2)/n \text{ sec}, \quad (1)$$

where B is the confining field, T the temperature, R the plasma radius, and n the particle density. Inserting typical values for our devices, $B = 3 \times 10^4$ gauss, $T = 10^5$ °K, $R = 1$ cm, $n = 10^{13}$ cm⁻³, we find $\tau_c \sim 0.6$ sec. Therefore, if virtually quiescent conditions can be found, confinement times of the order of a half second might be expected.

Bohm,⁷ on the other hand, has suggested that some sort of turbulence with randomly varying electrostatic fields exists even in "quiescent" plasmas and gives for the average macroscopic diffusion velocity

$$v_{\perp} \approx -\frac{4 \times 10^{18}}{nB} \nabla \phi \text{ cm/sec}, \quad (2)$$

where ϕ is the plasma pressure. This gives for a mean confinement time

$$\tau_c \sim (0.002 BR^2)/T \text{ sec}. \quad (3)$$

For helium under the conditions assumed above, this would give a confinement time of 600 μ sec. Even though Bohm and his collaborators adduced experimental evidence in support of this rate of diffusion, Simon and Neidigh⁸ at Oak Ridge have refuted their result and claim that there is good evidence that Bohm diffusion does not exist, at least in a "quiescent" plasma. Nevertheless it is reasonable to assume that fluctuating electric fields associated with instabilities and other cooperative phenomena can, under some conditions, cause enhanced diffusion across magnetic lines of force.

Heating

Ionization and preliminary *heating* of plasma confined in stellarator geometry is accomplished by making the closed tube of plasma the secondary of a transformer, as shown in Fig. 2. Flux changes in the transformer iron produce an axial electric field in the plasma which accelerates the electrons and to a much lesser extent the ions. The energy thus given to the particles is randomized and used in completing the ionization of the gas and "heating" the resulting plasma. It is to be emphasized that this *ohmic heating*

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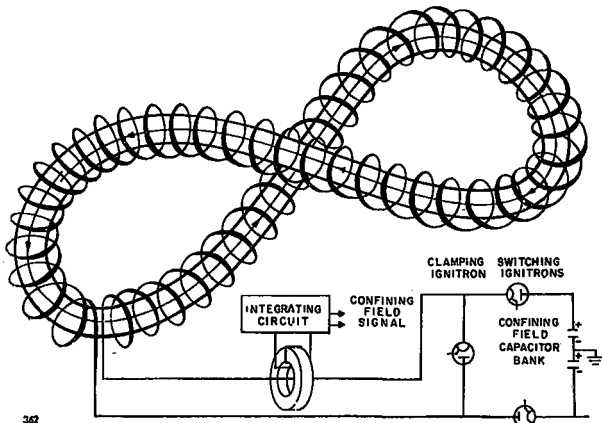


Figure 1. Distortion of torus into "figure-eight" geometry having a rotational transform, and simplified confining field circuitry

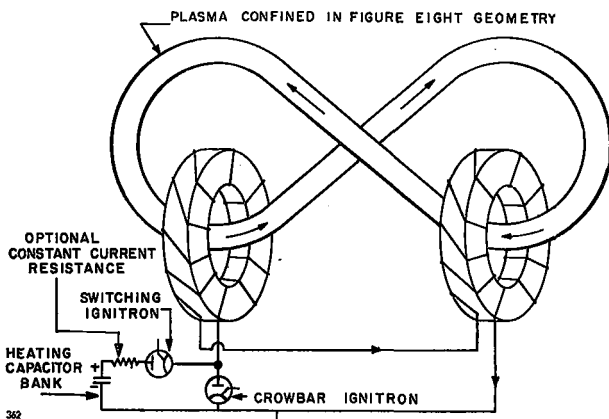


Figure 2. Ohmic heating apparatus and simplified circuitry

operates at very low fields (~ 0.1 v/cm) and makes no use of dynamical heating processes that are exploited in pinch-effect devices, nor is any use made of pinch fields produced by plasma currents for confinement. The existence of the hydromagnetic instability, predicted by Kruskal,⁹ which limits the maximum plasma current density to a definite value, and the fact that the conductivity of the plasma rises rapidly with temperature, place an upper bound on the temperature that can be achieved by ohmic heating.

When the heating field is applied to the discharge the initial conditions are, in general, a neutral hydrogen or helium gas pressure of the order of 10^{-3} mm Hg, pre-ionized to the extent of a few per cent. The temperature of the gas and plasma is essentially that of the walls of the apparatus. The applied electric field rapidly accelerates the initially existing electrons which in turn make collisions with other electrons, ions, and neutral gas atoms or molecules. As the electrons become energetic enough they will induce molecular break-up, radiative excitation and ionization in the gas. If the initial ionization is high and if the applied electric field is low, the electron energy distribution will remain essentially Maxwellian. The inelastic processes will then be executed by those electrons at the high energy end of the distribution.

Detailed calculations have been made by Berger *et al.*,¹⁰ on the ohmic heating of hydrogen and helium in stellarators. These calculations, in which the fractional ionization and electron and ion temperatures are followed, allow for the important atomic and single-particle processes that might take place in the discharge but assume that the energy distributions stay Maxwellian. Some doubt is cast on the applicability of these results by the fact that, in practice, the applied electric heating fields are large enough to distort the electron energy distribution away from Maxwellian. In particular, the group of runaway electrons (electrons which are gaining energy from the field faster than they lose energy by collisions) which arise early in the heating pulse are capable of more rapid ionization of the neutral gas than the main body of thermal electrons. At the same time, the runaway may be capable of exciting some cooperative mechanism that will transfer energy to the ions at a more rapid rate than the simple electron-ion Coulomb collisions assumed in the Berger model.

To make an exact calculation of the progress of a discharge, in which the electron energy distribution is allowed to be non-Maxwellian and in which cooperative processes are included, is of course impossible at the present time, since the nature of many of the processes is unknown. The best we can hope for in a comparison of the experimental results with heating theory is an indication of how important a part the unknown processes are playing in the heating.

EXPERIMENTAL APPARATUS

This and the accompanying papers^{2, 3} are concerned principally with results obtained in the operation of the B-1 stellarator. This machine uses "figure-eight" geometry and ohmic heating. A schematic diagram of the B-1 device with its associated diagnostic instrumentation⁸ is shown in Fig. 3. The discharge tube is fabricated from stainless steel, is 5 cm in diameter, and 450 cm in axial length. A short ceramic (alumina) section is welded into the otherwise conducting discharge tube at one point. This ceramic break pre-

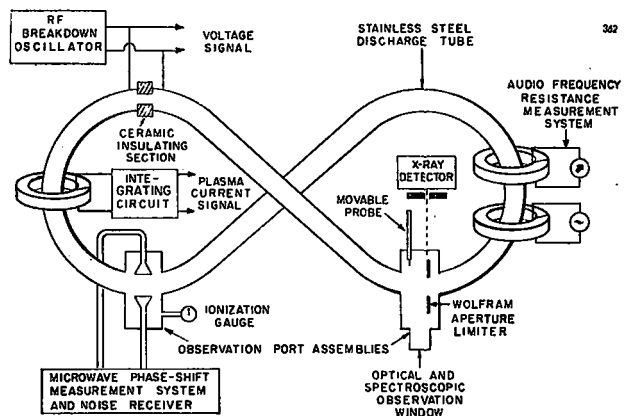


Figure 3. Schematic diagram of instrumentation on the Model B-1 stellarator. Not shown are the coils which produce the axial magnetic confining field, and the two iron transformer cores for ohmic heating (Fig. 2)

vents the discharge tube from short-circuiting the heating transformer and provides a convenient point for applying a 250-kilocycle radio-frequency pulse for initial breakdown.

Pulsed magnetic confining fields up to 30 kilogauss are used in the B-1 device. Energy storage for this field is obtained from a capacitor bank of 10^6 joules. Switching is performed by ignitrons of standard type.

Subsequent to the initial breakdown pulse, ionization is completed and the plasma is heated by means of a unidirectional axial electric field produced by two laminated iron transformer cores. The duration of this field is limited by saturation of the iron (~ 0.1 v-sec). Under normal operation the ohmic heating voltage waveform approximates a rectangular pulse; this is termed "constant-voltage" operation. Because of the Kruskal hydromagnetic instability which occurs at a definite critical current, it is sometimes useful to insert resistance in the primary circuit of the ohmic heating supply, thereby giving approximately "constant-current" operation at a point below the critical value. The ohmic heating field can be removed quickly at a pre-set time by means of a "crowbar" circuit, shown in Fig. 2, consisting of an ignitron switch to short-circuit the primary of the heating-field transformer.

In order to minimize direct wall bombardment by the plasma, and control the size of the discharge column, an aperture limiter was introduced in many experiments. The limiter is a wolfram mask with 3.2 cm diameter hole centred on the magnetic axis of the stellarator. The limiter has incidental uses in connection with diagnostic instrumentation, providing a reference potential for Langmuir probe measurements, and a localized target with high atomic number for the production of X-rays by fast electrons losing confinement from the discharge.

The instantaneous heating field is inferred from the voltage measured across the ceramic break in the stainless steel discharge tube. The plasma current is measured by means of a toroidally-wound pickup loop encircling the tube, the output of which is electronically integrated. These and other diagnostic signals are observed on multiple-channel synchronized oscilloscopes.

It is not possible within the scope of this paper to discuss in detail or justify the many types of instrumentation which have been used to analyze the progress of discharges under various conditions. Electron temperature is inferred from the plasma conductivity derived from observed heating voltage, plasma current, and aperture; from relative strengths of related singlet and triplet lines in the neutral helium spectrum; and from the amplitude of an induced signal coupled by the plasma between toroidally-wound transmitter and receiver coils, operating at a frequency low enough that skin effect can be neglected. Ion temperature is inferred from Doppler broadening of spectral lines of the working gas and of highly ionized impurities. Confinement effects are inferred from the maximum energy of X-rays pro-

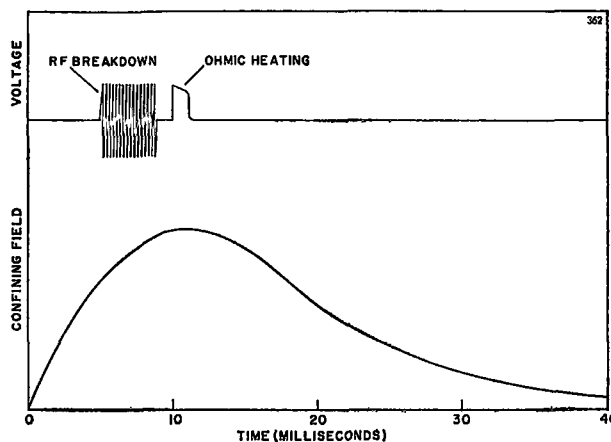


Figure 4. Relative time scales of axial magnetic confining field and voltage externally applied to stellarator loop

duced by fast electrons; from time variations in electron density, derived from phase-shift of a transmitted millimeter microwave beam¹¹; and from Langmuir probes located outside the active discharge aperture. Instability processes of various types and wall effects are inferred from spectral lines of impurity atoms; from streak photography; and from emission of X-rays and high-level non-thermal microwave noise. Langmuir (electric) and magnetic probes have not been found useful in the active region of the discharge. Because of the rotational transform, an obstacle such as a probe intercepts in principle all plasma outside the magnetic surface adjacent to the inner tip of the obstacle, thus becoming an aperture limiter. While probe studies were nevertheless possible in early devices in which high impurity levels existed because of wall outgassing, it has been found that the high plasma temperatures and abundant runaway electrons of our baked devices consistently destroy the probe in one or two pulses.

The results of early experimentation led to the conclusion that the behavior of discharges in devices of this type was completely dominated by outgassing of the walls if conventional vacuum systems were used. Therefore, since 1956 all devices have been constructed so as to be fully bakable to 450°C. With baking, a base pressure of the order of 2×10^{-10} mm Hg has been achieved, and the influx of impurities has been reduced by about two orders of magnitude. In spite of these efforts, material from the wall is still a significant factor in the behavior of these devices under most operating conditions. During operation, spectroscopically pure gas is introduced continuously through a controlled leak to maintain an operating pressure between 10^{-4} and 10^{-3} mm Hg. While the behavior of hydrogen and deuterium discharges has been studied in some detail, more extensive work has been done with helium, because of better characteristics for optical spectroscopic analysis and greater freedom from complex molecular and chemical phenomena.

The time scale and sequence of operation is shown in Fig. 4. The magnetic confining field is essentially constant during the interesting portions of the dis-

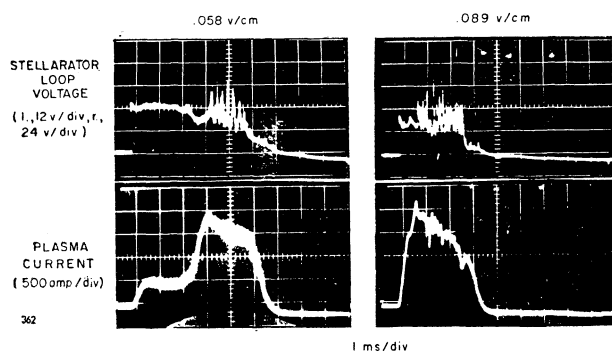


Figure 5. Representative constant-voltage ohmic-heating discharges in helium
Confining field, 27 k-gauss; pressure 5×10^{-4} mm Hg

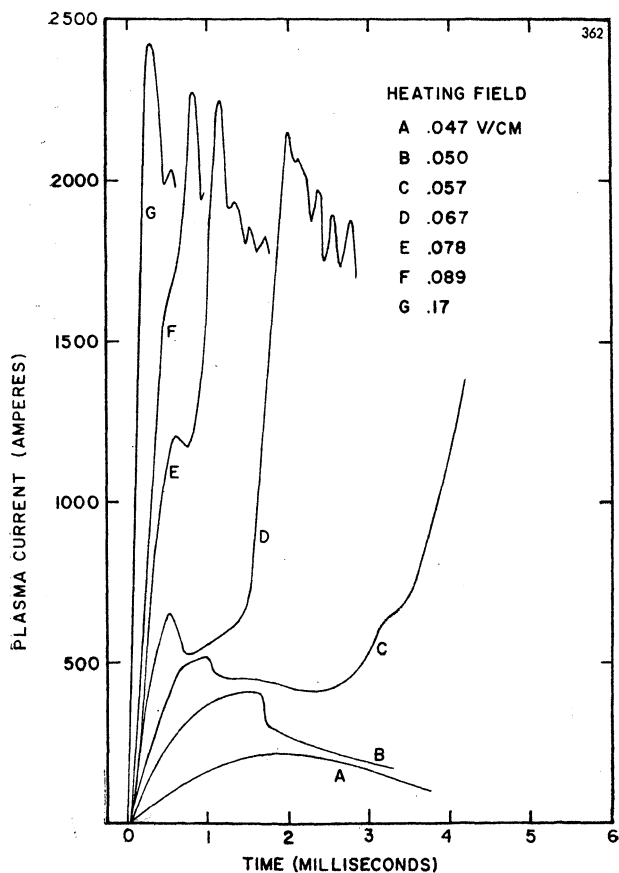


Figure 6. Development of current in helium discharges for various heating fields
Confining field, 27 k-gauss; pressure, 5×10^{-4} mm Hg

charge. The timing of all operations is controlled by pre-set counters driven by a 100-kc/sec master oscillator. Operation is limited to about one pulse per minute by capacitor bank charging and heat dissipation of the field coils.

EXPERIMENTAL RESULTS

In this section the major experimental observations at various stages of the discharge are summarized. The principal variables are the value of confining field (10 to 30 k-gauss), the ohmic-heating field (0.04 to 0.5 v/cm), and the initial gas pressure (10^{-4} to 10^{-3} mm Hg). Other parameters are the

amplitude, duration, and timing of the radio-frequency breakdown pulse and the shape of the heating field waveform (constant-current or constant-voltage operation, and termination by crowbar). The following discussion refers to helium discharges unless otherwise stated.

The Current Rise

Upon application of the ohmic-heating field, the plasma current and electron density rise rapidly. Representative cases of current and voltage behavior for constant-voltage operation are shown in Fig. 5. Figure 6 shows the current rise for several values of heating fields. At high heating fields, the current reaches the Kruskal instability limiting current in 100 μ sec or less. The limiting current for the B-1

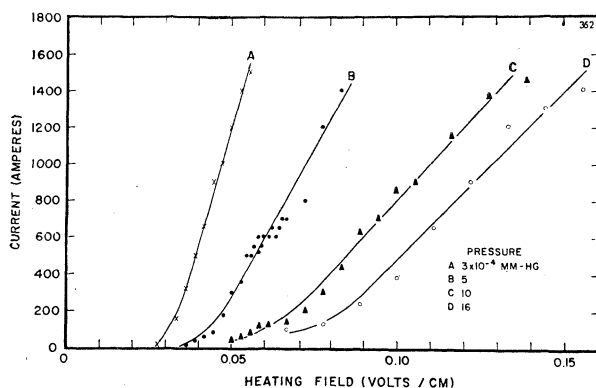


Figure 7. Maximum of first current plateau as a function of heating field and pressure
Confining field, 27 k-gauss; helium gas filling

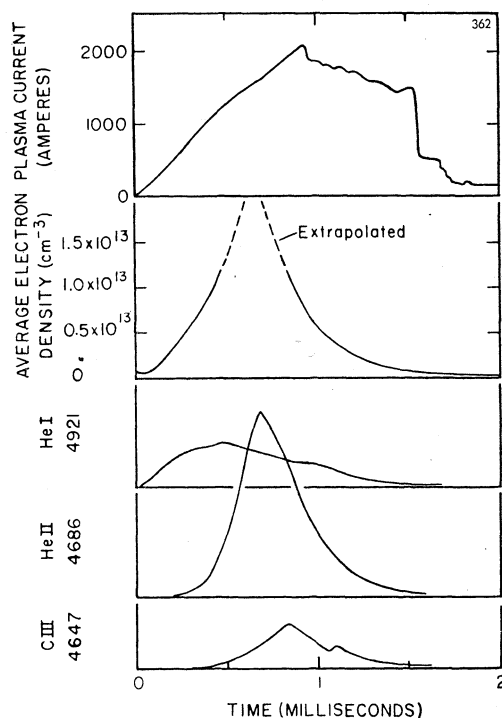


Figure 8. Plasma current, average electron density, and spectroscopic lines during a low-pressure, constant-voltage discharge in helium. The heating field (.067 v/cm) lasts about 4 msec.
Confining field, 27 k-gauss; pressure, 3×10^{-4} mm Hg

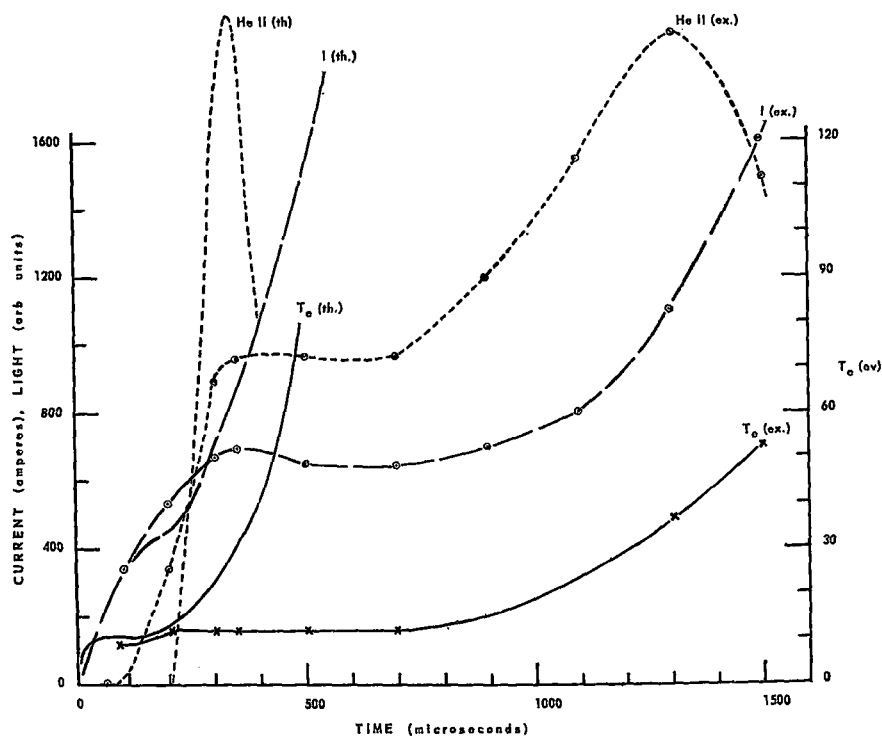


Figure 9. Comparison of experimental plasma current, ionized helium light, and electron temperature data with theoretical values
Heating field, 0.11 v/cm; confining field, 27 k-gauss; helium 8×10^{-4} mm Hg. For this case, the plasma aperture was estimated to be 8 cm^2

device with 4.1 cm diameter geometrical aperture is about 2200 amp at a confining field of 27 k-gauss. At moderate fields the current typically rises to a value (< 500 amp) well below the Kruskal limit, remains at this plateau value for as much as several milliseconds, and then rises rapidly to the Kruskal limit. In general, the second rise always proceeds to the Kruskal limit although at low heating fields (Fig. 6, case A) the field ends before a second rise is evident. The plateau currents are essentially independent of confining field, and are shown as a function of heating field and pressure in Fig. 7. The plateau is accompanied by X-ray production and intense non-thermal microwave noise generation.

Typical spectroscopic data obtained by Photomultiplier techniques are shown in Fig. 8. The neutral helium line peaks early in the current rise and then falls slowly. The slowness of fall may result from the influx of cold gas from the external portions of the vacuum system, in particular the observation port, and perhaps also from wall outgassing. Ionized helium light peaks slightly later during the current rise and then falls to low intensity. Spectroscopic evidence indicates first ionization in excess of 95%, and probably a high degree of second ionization. Spectral lines of impurity atoms, such as C^{III} 4647 Å and O^{II} 4415 Å, emerge well before the Kruskal instability current is reached. Preliminary observations of Doppler broadening at the time of the current plateaus of Fig. 6 (this feature is barely visible at about 70% of maximum current in Fig. 8) indicate ion temperatures far in excess of what would be expected from

ohmic heating alone. These measurements, of great potential significance, must be carried much farther before dependable conclusions can be drawn.

In Fig. 8 the average electron density, inferred from 8.6 mm micro-wave phase-shift data, begins to fall before the Kruskal critical current is reached, indicating imperfect confinement of the plasma.

A comparison of theoretical calculations¹² with the observed time dependence of plasma current, electron temperature, and ionic (4686 Å) He^{II} light is shown in Fig. 9 for a typical case where two current plateaus are observed. The temperature was inferred from plasma conductivity data. The agreement between theory and experiment is good in the early phase of the discharge. The theory predicts the existence of the first current plateau, and approximately predicts the observed value of current and electron temperature. However, the duration of the first current plateau is considerably longer than theoretically predicted; this effect is presumably caused by the influx of cold gas into the discharge region. Furthermore, some He^{II} is observed much earlier than theory predicts, at a time when first ionization of helium is not complete.

Operation at the Kruskal Limiting Current²

When the current reaches the Kruskal kink-instability critical value, both plasma current and voltage show violent fluctuations, as indicated in Figs. 5 and 8; the average current then decreases somewhat with time. No X-rays are produced at this time, indicating that single-particle confinement is too short for runaway electrons to reach high energies.

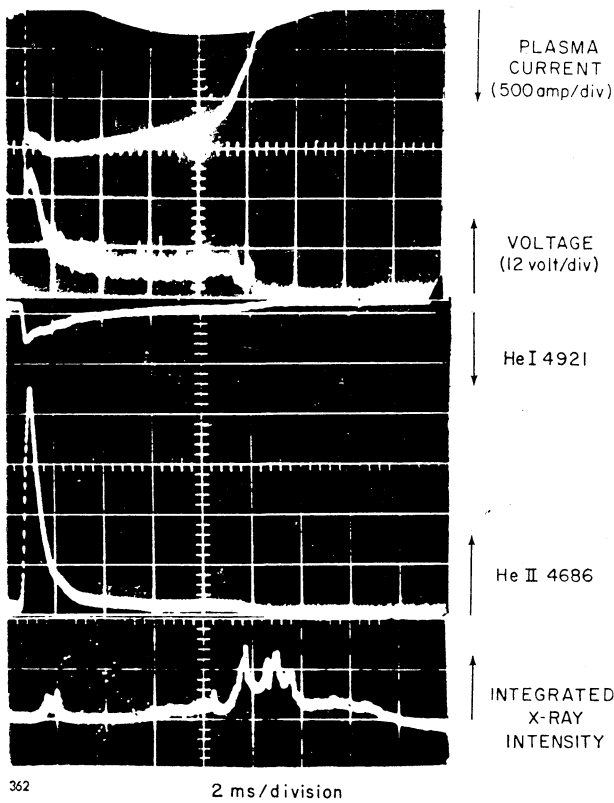


Figure 10. Representative constant-current discharge in helium. Confining field, 27 k-gauss; pressure, 5×10^{-4} mm Hg

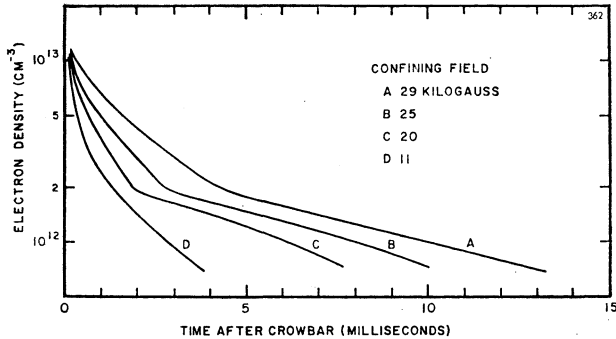


Figure 11. Variation of average electron density during constant-current heating. Current, approx. 1000 amp; helium, 5×10^{-4} mm Hg

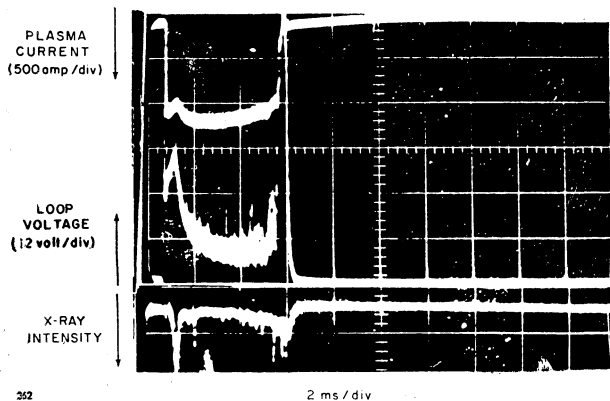


Figure 12. Constant-current discharge showing abrupt current end. Confining field, 20 k-gauss; helium, 5×10^{-4} mm Hg

Depending on the outcome of the competition between the driving of ions into the walls and the resulting intense outgassing of the walls, the charged particle density either falls, as in Fig. 8, or remains high. The time constant for decay of electron density in Fig. 8 is about $300 \mu\text{sec}$. Spectral lines of impurities (principally carbon, oxygen, and hydrogen) are very intense, particularly in the case where outgassing dominates and the electron density remains high. Although no quantitative measure of the abundance of impurity ions in the discharge exists, it is clear that they are a major factor even under ultra-high vacuum conditions.

Operation at "Constant Current"

By placing a relatively high resistance in series with the heating-field power supply, it is possible to limit the plasma current to a value well below the kink limit. Typical current and voltage behavior is shown in Fig. 10. Under these conditions the charged particles are again rapidly lost from the discharge. Figure 11 shows the variation in electron density during these constant current discharges.

A brief X-ray burst appears at the time of the current rise. As the discharge progresses and the charged particle density falls, there is at first little and then increasingly intense X-ray production. It is probable that a significant part of the current in the final stages of the discharge is carried by runaway electrons. In the usual case, as the ohmic-heating transformer cores saturate, the current falls slowly, often in a series of small steps accompanied by X-ray bursts. Occasionally, the current and electron density both drop abruptly, with a consequent sudden rise in the heating voltage. This effect, illustrated in Fig. 12, is presumed to be some type of plasma instability, perhaps associated with runaway electrons.

At sufficiently high initial gas pressures the wall emission rate is high enough to maintain the charged-particle density in the discharge. To study wall emission effects, data similar to Fig. 11 were taken as a function of pressure. Electron density loss rates, tangents to observed decay curves at 5×10^{12} electrons/cm³, are shown in Fig. 13 for hydrogen. An extrapolation to zero pressure suggests a confinement time of the order of $100 \mu\text{sec}$ in the absence of wall feedback effects.¹³

The current and voltage data of Fig. 10 can be used to compute plasma resistivity if an effective plasma diameter is assumed. This diameter can be estimated from the Kruskal instability current or from geometrical considerations, these being in satisfactory agreement.² For the Model B-1 stellarator the effective diameter without wolfram limiter is 3.6 cm with an estimated accuracy of 15%. One infers the electron temperature, using the theoretical resistivity relationship which assumes Maxwellian electron distributions,¹⁴

$$\eta = K (\ln \Lambda) T_e^{-\frac{3}{2}} \quad (4)$$

(the electron kinetic temperature T_e is in degrees Kelvin; $\ln \Lambda$ is a slowly varying function of tempera-

ture and density of the order of ten in our experiments; the constant K is 6.5×10^3 ohm cm for hydrogen, 11.1×10^3 for doubly-ionized helium). For the data of Fig. 10 the resistance is relatively constant at about 5 milliohms during the latter two-thirds of the discharge, corresponding to a temperature of about 90 electron-volts. This computation of temperature is subject to question because a significant fraction of the total current may be carried by runaway electrons, and indeed the "thermal" electrons may not have a Maxwellian velocity distribution. Furthermore, the actual current channel may be broken up or distorted by cooperative processes. Low-frequency ac conductivity measurements cannot be made during heating because fluctuations in the heating current produce too high a noise level.

Electron temperature measurements based on the relative intensities of corresponding singlet and triplet lines in the helium spectrum are inaccurate because of poor knowledge of the excitation cross-sections, the non-Maxwellian distribution, and low experimental light intensities. However, such measurements give better than order-of-magnitude agreement with resistivity data.

Ion temperatures, from Doppler line widths, are difficult to measure during heating because of the low light intensity. Under typical conditions, He^{II}

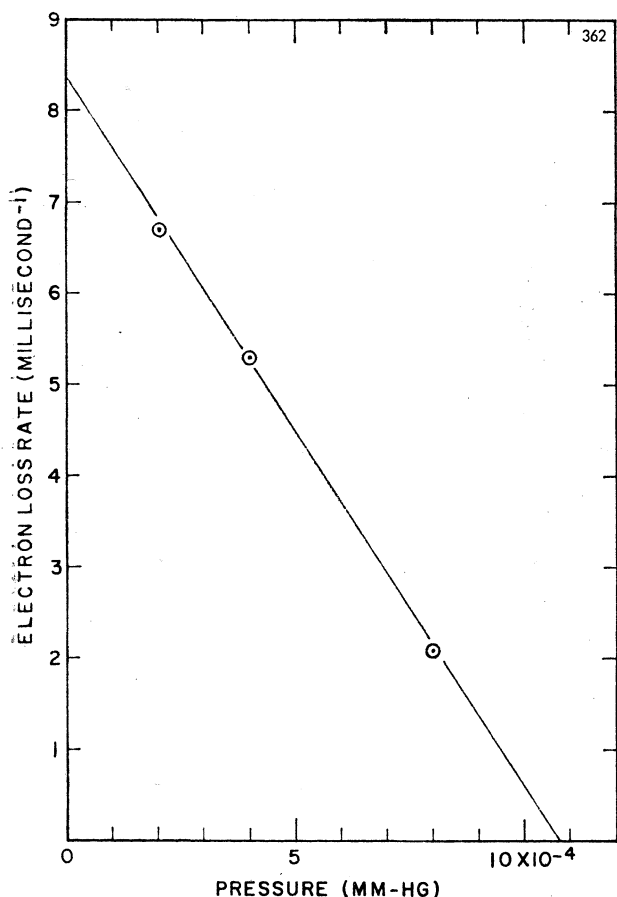


Figure 13. Electron density loss rates during heating as a function of operating pressure
Heating current, 1500 amp; confining field, 27 k-gauss

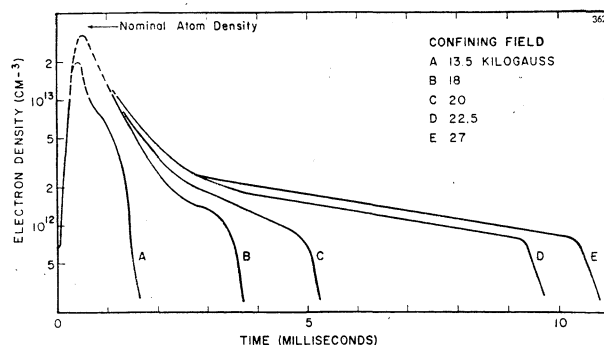


Figure 14. Average electron density following crowbar termination of heating field
Heating field (0.2 v/cm) applied 0.75 msec prior to crowbar; helium, 5×10^{-4} mm Hg

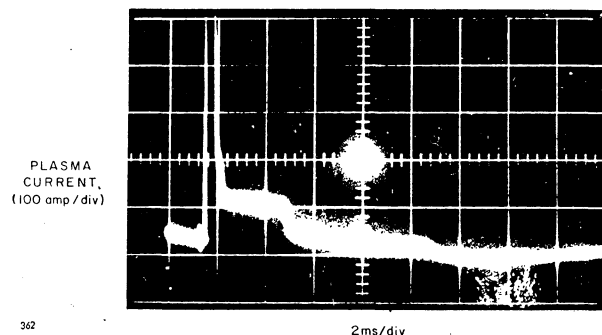


Figure 15. Stepwise decay of plasma current following removal of heating field by crowbar 1.8 msec after start of oscilloscope trace
Concave curvature of baseline is instrumental; current reaches zero 12.6 msec after start of trace. Heating field, 0.3 v/cm; confining field, 27 k-gauss; helium, 4×10^{-4} mm Hg

4686 \AA appears cold ($< 5 \text{ eV}$) in the later stages of the discharge when one might expect the temperature to be a maximum. The possibility of mass motion, due to cooperative processes, and the possibility that cold gas continually entering the discharge may contribute disproportionately to the radiating ions limit the validity of these observations. Light observations are normally made transverse to the stellarator axis, an unfavorable geometry for observing volume rather than surface radiation.

Discharge Behavior after Heating

Many discharges terminate when the charged-particle density falls so low that the electron energies can no longer be moderated and all particles run away. If wall emission has been high enough that substantial density is left when the heating field ends, the density falls rapidly at first and then more slowly, with a time constant of the order of a millisecond. To retain a significant density at the heating pulse end, the field can be removed by crowbar before much gas has been lost and before the walls are heavily bombarded. Typical data are shown in Fig. 14. Again the density drops quickly at first and then more slowly. Decay time constants of the order of 6 msec have been observed under these conditions. However, low-frequency conductivity measurements made at this time indicate a completely cold plasma. A very large

prolonged burst of X-rays is observed some 10 msec after the discharge, when the confining field is between one-half and one-third of its peak value.

A very striking phenomenon, characteristic of the crowbarred heating-field, is that the current does not fall abruptly, but rather decays slowly in a series of abrupt "steps" and plateaus. This effect is shown in Fig. 15. The steps are accompanied by X-rays and microwave noise. For some conditions the electron density is observed to increase suddenly, by as much as a factor of two, at the time of a current step. Since the after-current would appear to consist principally of runaway electrons, this period of the discharge, like the rise of current, may be controlled largely by associated plasma instabilities. These effects are considered in greater detail in the accompanying paper.³

Comparison of Hydrogen and Helium¹³

The behavior of the B-1 device operated with the two atomic species is qualitatively similar. The rate of decay of the plasma density during ohmic heating is from two to five times greater in hydrogen than in helium, presumably because of the greater binding of hydrogen on the walls. The plateaus on the rise of the current are not observed in hydrogen. A further difference occurs during the radio-frequency breakdown discharge. Hydrogen is removed very rapidly during the discharge, to the extent that the ohmic heating discharge is inhibited for several milliseconds afterwards. Helium, on the other hand, shows negligible net loss of gas during the breakdown discharge. This difference may result from dissociative recombination and charge exchange processes in the feebly-ionized radio-frequency discharge. No significant differences between hydrogen and deuterium have been detected.

CONCLUSIONS

Although many details of the operation of stellarators are yet to be explained in full, most general features of the observations described above appear to be understood. One of the most clear-cut results obtained in the operation of these devices is the effectiveness of the figure-eight geometry in providing single-particle confinement. Runaway electrons persist for many milliseconds after the heating pulse terminates, as evidenced by the late burst of X-rays which occurs when the confining field has diminished markedly. This persistence is clear evidence that the rotational transform of the stellarator produces confinement. These electrons make about 5×10^5 circuits of the loop during a time when there is negligible axial current along the discharge tube to produce any rotational transform, a phenomenon which would not be possible in a simple torus, where the drifts are of the order of one gyration radius per revolution.

The most significant measurement of plasma confinement appears to be the confinement time during ohmic heating in hydrogen, obtained from Fig. 13. The result, approximately 120 μ sec at 27 k-gauss, is

much shorter than the classical collision diffusion time and is nearer the value predicted by Bohm's equation, a result which may be fortuitous. The confining field dependence is not yet known. We have no knowledge of the process that is responsible for this rate of plasma disappearance from our devices. The runaway electrons or non-Maxwellian particle distributions that exist during ohmic heating may produce plasma oscillations which give rise to enhanced diffusion across lines of force. Also there exists the possibility of interchange instability or higher modes of the kink instability of Kruskal. Evaluations of the ratio of material pressure to magnetic energy density, a parameter which appears in the theory of the interchange type of hydromagnetic instability,¹⁵ yield values of the order of 10^{-5} for discharges under various conditions. Theoretical estimates of the critical value of this parameter for the B-1 device are not available because of the complex geometry. While the data are not inconsistent with the occurrence of an interchange type of instability, its presence cannot be assumed without some more direct evidence.

The observations on the plasma decay after the ohmic heating is terminated unfortunately give no good evidence as to the confinement of a "quiescent" plasma. The rapid fall in electron temperature after the end of the ohmic pulse is clear evidence that enough impurities have entered the plasma to catalyze recombination. However, the runaway electrons which continue to exist in the plasma during this period have enough energy content to keep the ionization process going and maintain the plasma in spite of recombination. There is some difficulty in explaining the rate of ionization, but since the transverse velocities of runaway electrons may also be large, the runaway electron flux effective in ionization could be considerably greater than that detected by axial current measurements.

The existence of runaway electrons and non-Maxwellian particle distributions makes detailed comparison with the simple theory of *ohmic heating* unrewarding, but the general behavior of the ionization and heating process is about as predicted. It has been shown to be possible with relatively low electric fields to ionize a gas almost completely and to heat it to maximum temperatures of the order of 100 electronvolts in spite of cooperative processes that limit the confinement time during heating and in spite of an appreciable influx of impurities from the walls.

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