The Divertor, a Device for Reducing the Impurity Level in a Stellarator

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The divertor is a device, first proposed by L. Spitzer,1 for averting contact between the hot ionized gas and the wall of the main discharge tube. An outer cylindrical shell of magnetic flux is conducted from the main discharge tube into an auxiliary chamber. Ions and electrons diffusing outward from the main plasma enter this shell and follow along the magnetic lines of force to strike a collector plate in the auxiliary chamber rather than the wall of the main discharge tube.

In the Stellarator experimental program, it became apparent rather early that the character of the discharges in helium was dominated by the influx from the walls of impurities of higher atomic number. In the unbaked B–1 Stellarator,2,3 a correlation was observed during the course of the discharge between the drop in electron temperature and the spectroscopically observed radiation from impurity ions. Measurement of the Doppler width of the λ4686 Å line of ionized helium indicated that inelastic collisions with incoming cool impurity ions were responsible for depressed ion temperatures.

Major strides have been made toward overcoming the impurity problem by extended bakeout at 400°C and by use of other ultra-high vacuum techniques.2,3 A second method for impurity reduction is to use a divertor. The divertor was originally conceived as a solution to a temperature distribution problem; but a device which protects the walls from hot ions can be of use in reducing impurity influx. It is the description of a divertor, the design, and an experimental measure of effectiveness of impurity reduction which will comprise the body of this paper.

THEORY

A divertor introduces an important change in the topology of the magnetic field in a stellarator as is evident from the preceding description and Figs. 1 and 2. The main discharge is, in effect, surrounded by a protecting sheath or scrape-off layer, which leads to an auxiliary chamber. Hot ions diffusing radially outward from the main discharge travel preferentially along the sheath into the collector plate and a reduced number of them will strike the walls of the main discharge tube. Similarly, impurity atoms which are released at the walls of the main discharge tube by photon bombardment (or by those ions and electrons which succeed in traversing the sheath) will become ionized either in the sheath or near the boundary between the sheath and main discharge, and may be led into the auxiliary chamber.

Any beneficial action of a divertor hinges on the possibility of reducing the back flow of those impurities which will be released at the collector plate. Several processes act to reduce this backflow. Most of the impurity atoms released from the collector plate will be neutral and most of the impinging helium ions will be released to the chamber as neutral atoms. For the divertor used in these experiments, the characteristic time for the return of neutral atoms to the discharge is 27 milliseconds, which is long compared to the duration of the discharge. For discharges of much longer duration it is possible, in principle, to pump these atoms away; for the present experiments the required pumping speed is impossibly large and the available speed negligible by comparison. As a result, the pressure of these neutral atoms in the divertor chamber increases as the discharge proceeds. The rate of backflow of the neutral gas into the main discharge region is then determined by the gas kinetic conductance of the divertor-tube opening and the divertor pressure.

A detailed calculation shows that if the thickness of the sheath were sufficiently great and if the return process were solely one of neutral gas flow, this divertor would reduce the impurity level in the discharge by factors of 220 and 30 at times 100 microseconds and 1000 microseconds after the start of the discharge.

While it is unlikely that impurity atoms and helium atoms will leave the collector plate as ions, it is possible that these atoms will be ionized in the divertor by the incoming ions and electrons. These ions could then flow rapidly back into the discharge. However, some of them will be reflected by the strong magnetic mirror at the entrance to the main discharge tube. Those ions which succeed in passing through the mirror are still in the volume of the protective sheath, and may again reach the collector plate before diffusing across
lines of force into the main discharge. A detailed analysis of the ion backflow has not been made.

A smaller reduction in impurity level than that predicted by the simple neutral backflow approach may thus be expected with either inadequate sheath thickness or ion backflow. In such cases there will be an appreciable number of cool helium atoms returning quickly to the discharge and for these cases it is instructive to investigate the expected time dependence of the light from He++. A phenomenological analysis which furnishes an instructive fit to the experimental data on the divertor-no divertor comparison may be obtained as follows. Let \( n_0 \) be the number of neutral helium atoms initially in the tube divided by the volume of the discharge column, and let \( n_1, n_2, \) and \( n_3 \) represent the number density of neutral He, He+, and He++ as functions of time. Then we have

\[
\frac{dn_1}{dt} = \gamma \xi (n_2 + n_3) - a_1 n_1, \\
\frac{dn_2}{dt} = -a_2 n_1 - \xi n_1 + a_1 n_1, \\
\frac{dn_3}{dt} = a_3 n_1 - \xi n_3.
\]

(1)

where \( a_1 \) is the ionization rate for neutral He to He+, \( a_2 \) is the ionization rate for He+ to He++, \( \xi \) is the rate at which charged particles leave the discharge as a result of diffusion, instabilities, etc., and \( \gamma \) is the fraction of ions which re-enter the plasma as neutral atoms after hitting material walls. The rate coefficients \( a_1, a_2, \) and \( \xi \) are assumed independent of time. In the application of the analysis to the experimental data, it will be assumed that the spectral intensity of a line is proportional to the number density of the corresponding species. All spatial variations of these quantities are neglected.

For operation with no divertor, \( \gamma \) is assumed to be unity. The total number of ions and atoms is constant, and in time an equilibrium plateau is reached. If \( a_1 \) is much greater than \( \xi \), it is readily seen from Eq. (1) that the value of \( n_1 \) for the plateau phase is given by

\[
n_1 = n_0 \xi / (a_2 + \xi).
\]

(2)

If in addition to the condition \( a_1 \gg \xi \) we take \( a_1 \gg a_2 \), then all the helium is ionized to He+ before any appreciable amount of second ionization occurs and \( n_1 = n_0 \). The peak-to-plateau ratio for \( n_1 \) is thus \( 1 + (a_2/\xi) \), so that an observed peak-to-plateau ratio of 3.0 would predict \( a_2/\xi = 2 \). A more detailed solution of Eq. (1), using the assumption that \( a_1 = 10a_2 \) (as indicated in the analysis by Berger and Frieman), for 80 ev electrons) gives the more precise result \( a_2/\xi = 3.1 \) for a peak-to-plateau ratio of 3.0.

We now consider the behavior of \( n_1 \) with the divertor operating so that \( \gamma \ll 1 \). Using approximations based on the inequalities \( a_1 \ll a_2 \) and \( a_1 \ll \xi \), the solution of Eqs. (1) for \( n_1 \) is

\[
n_1 = \frac{n_0}{a_2 + \xi} e^{-(a_2 + \xi) t} + \frac{\gamma}{a_3 + \xi} e^{-(a_3 + \xi) t}\]

(2)

where \( n_0 \) is again the initial density of neutral He. For \( 0 < \gamma < 1 \), the decay of singly ionized helium is characterized by two exponential terms. If \( n_1 \) is plotted against time on semi-log paper, the slopes for the two components are simply the exponents in Eq. (2). The measurement of these two slopes plus the peak-to-plateau ratio for the no-divertor operation gives three numbers from which one may determine the ionization rate, \( a_2 \), the confinement time, \( 1/\xi \), and the measure of divertor effectiveness, \( \gamma \).

**DESIGN**

For the experiments reported in this paper, the B-65 Stellarator was used. An illustration of this device with its divertor is shown in Fig. 1. Details of the B-65 machine other than the divertor are given elsewhere. The B-65 geometry is a race-track, and the machine is equipped with helical windings. However, the use of helical windings reduces the amount of scrape-off (defined below) furnished by the divertor, and for this reason, the more significant data regarding divertor action were taken with the helical windings not energized. A rotational transform for the magnetic field was then provided entirely by the ohmic heating plasma current flowing along the lines of force. A quarter-section of the divertor is shown in Fig. 2. The coils of the divertor are electrically in series with the confining field coils, but polarized so that current passes through the center coil of the divertor in the reverse direction. The aperture of the machine is defined as the radius of the largest flux tube which passes unmolested through the divertor, this radius being measured in a section of the machine containing the uniformly wound solenoid. The intersection of this flux tube with a plane through the axis of the coil system is called the diverted line. For each machine arrangement, there is a similar line associated with the smallest flux tube which intersects or is tangent to the vacuum wall at some point in the machine. This line is called the limiting line. The region between these two flux tubes is called the sheath or scrape-off region, and the distance between these two lines is called the scrape-off distance.

The magnetic design of the divertor was performed on a special resistance analogue, capable of accurately representing axially symmetric magnetic fields. The theory and operation of this analogue have been described previously. A group of critical characteristics was met in a trial and error design procedure.
These characteristics were that:
(a) the radius of the aperture should be about 1 in.;
(b) the magnetic field intensity at the center of the divertor should not be less than 20% of the value in the uniform solenoid;
(c) the limiting line should not touch any part of the vacuum wall until well within the divertor chamber;
(d) the distance between the diverted line and the walls of the vacuum system as it passes through the throat should be several radii of gyration for the ions at the local field strength;
(e) the width of the throat should be kept small to minimize the backflow of neutral atoms;
(f) the mirror ratio of the throat should be kept high to reduce the backflow of charged particles, but
there should be no mirror effect for particles entering the divertor from the main discharge tube; and

the coil location and required current density must allow reasonably easy manufacture.

In the B-65 Stellarator, the radius of the limiting surface is 1.59 in. in the sections containing a uniform solenoid, resulting in a scrape-off distance of 0.55 in. When the helical windings are energized, the scrape-off distance is reduced to 0.26 in., because of the deformation of the cross sections of the magnetic surfaces from circles into trefoils. These values of scrape-off distance are derived from the analogue data. Practical difficulties of carrying windings around ports and other obstructions make achievement of the ideal magnetic configuration rather difficult and the actual scrape-off distances are probably smaller than these.

The dimensions of the divertor and the general form of the walls are indicated on the scale drawing of Fig. 2, which shows the magnetic configuration. The field strength at the center is 41% of the value in the sections of the machine containing a uniform solenoid. The volume of the divertor is 48 liters, and the gas-field strength at the center is 41% of the value in the sections containing a uniform solenoid. The magnetic configuration rather difficult and the actual scrape-off distances are probably smaller than these.

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The divertor-limiter comparison was accomplished by taking sets of data alternately for the two cases. A particular study would be taken first with the divertor and the limiter retracted. Immediately thereafter, the corresponding data would be taken with the divertor reverse coil not energized and the limiter in place.

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The machine base pressure was about $2 \times 10^{-4}$ mm Hg, and the operating pressure was $1 \times 10^{-4}$ mm Hg of helium. A confining field of 20,000 gauss and an ohmic heating field of 0.24 v per cm resulted in a plasma current of approximately 3500 amp. This amount of current is 45% of the calculated limiting current for the Kruskal $m = 1$ instability. A 250 kc rf electric field was applied for pre-ionization. Additional information on operation of the B-65 machine is given elsewhere.

Identification of the important impurities and their stages of ionization was made from photographs of the spectra. These were taken on an f/2.8 stigmatic gratingspectrograph with reflection optics, after a design by Dr. A. B. Meinel. The spectrograph has a first-order dispersion of 20 $\AA$/mm. The first-order spectral slit width of 0.3 $\AA$ used in these experiments was less than the Zeeman and Doppler widths of the spectrum lines. Exposures of 15 pulses on Kodak 103a-0 spectroscopic film were required.

Time-resolved intensity measurements were made on H$^+$ 5868 $\AA$, H$^+$ 656275 $\AA$, and on selected impurity lines of carbon, nitrogen and oxygen. For this purpose a Jarrell-Ash monochromator was used with an RCA 1P28 photomultiplier at the exit slit. This is an 0.5 meter instrument with a 1200 mm$^{-1}$ plane grating 5 cm in width, used in second and third orders. The photomultiplier signal was displayed on a Tektronix Type 531 oscilloscope and photographed with a DuMont Polaroid camera.

Spectral profiles were also obtained with the monochromator. Data were taken in scans of 20 pulses with successive signals at about 0.1 $\AA$ intervals. In a compromise between resolution and illumination, a resolving power of 15,000 was used. The light was observed through quartz windows in the axial direction parallel to the confining magnetic field. Ion temperature and intensity measurements were made on the divertor leg of B-65, while photographs were taken both through the divertor leg and through the opposite leg.

EXPERIMENTAL RESULTS AND DISCUSSION

Spectrograms

An initial spectrographic survey produced profuse spectra of carbon, nitrogen, and oxygen in addition to helium. Figure 3 is a reproduction of a divertor-limiter pair of spectra taken at the beginning of the experiment. The spectrogram was made on a 10 in. strip of film which has been reproduced here in three sections. Selected strong impurity lines which were later studied with time resolution have been designated in addition to some of the helium lines. The decreased density of the impurity spectra with the divertor is readily apparent in the original film. A notable exception to this trend for the impurity lines is the enhancement of the O$^+$ multiplet 3s $^3$S$^-$ 3p $^3$P in the ultra-violet. In the early operation of the B-65 device, the walls were strongly contaminated with impurities. Under these conditions, the higher electron temperature necessary for the production of strong spectra from highly ionized impurity atoms was achieved only by using the divertor to increase the purity.

The arc lines of chromium appeared at the top and bottom edge of the spectra indicating the sputtering of metal from the limiter and, to a lesser extent, from the divertor. Spectra taken from the opposite leg of the machine were similar except for the absence of the chromium lines.

† The authors are indebted to D. T. Scag for a very clean mechanical design.
Time-resolved Intensities of Spectral Lines

Tracings of the light signals for various impurity radiations and helium are shown with the corresponding traces of plasma current in Fig. 4. The time scale for the light signals is identical with that for the plasma current. The ordinates indicate the relative photomultiplier signals for divertor and limiter operation, and in general are different for each transition. In comparing each pair of light signals, allowance must be made for the variation of ionization and excitation cross sections with electron temperature. The electron temperature should increase markedly with relief from impurity influx. Unfortunately, neither the required cross sections as a function of electron energy nor the electron temperature in the plasma are known. Electron temperatures of the order of 20 ev are obtained from plasma resistance measurements; but since the measured resistance includes an unknown contribution from the impedance arising from cooperative phenomena, the technique is not a reliable diagnostic tool. A better clue comes from the strong signals in the O\text{v} spectrum which indicate appreciable numbers of electrons with energies exceeding 77 ev, the energy required to remove the fourth electron.

When the mean electron energy is several times the ionization energy of an ionic species, the excitation and ionization cross sections for the species are not strong functions of the electron temperature. For the divertor–limiter comparison, we thus expect the amount of impurity influx to be better described by the light from the lower stages of ionization. The spectra in Fig. 4 show a factor of 2 to 3 reduction in light from the singly ionized impurities. It seems likely that the divertor reduced the impurity level by at least this factor.

It is believed that the impurities are ionized first near the scrape-off region and that the highest stage of ionization is found primarily in the plasma core. The observed ionization rates and derived confinement time discussed later agree qualitatively with this picture. In Fig. 4, the intensity of the O\text{v} line is reduced by a factor of 10 when the divertor is used, indicating that the purity of the central region may be higher than that indicated by O\text{IV} for the scrape-off region. Supporting evidence for this view comes from the measured positive ion temperatures discussed below.

Positive Ion Temperatures

Ion temperatures derived from Doppler broadening of the He\text{II} 4686 Å and O\text{v} 2781 Å lines are shown in Fig. 5 for the two cases as functions of time during the ohmic heating pulse. The line profiles were compared with the calculated Doppler broadened Zeeman
structure, and a correction was made for the finite spectral slit width of the monochromator. The resultant temperatures are quite sensitive to these corrections and are accurate to about 10 ev; the divertor–limiter comparisons should have a relative accuracy of perhaps 5 ev. The increased ion temperatures observed with the divertor are attributed to the reduction in the influx of cool impurity ions which would otherwise cool the ions in the discharge, directly by inelastic collision and indirectly by lowering the electron temperature.

Line scans on O\textsuperscript{+} \lambda 4415 \text{Å} indicate the O\textsuperscript{+} ions to be at about the same temperature as He\textsuperscript{+}. From O\textsuperscript{IV} \lambda 3063 \text{Å} and the N\textsuperscript{IV} multiplet 3s \text{S} \textsuperscript{2} – 3p \text{P} \textsuperscript{1} \text{P} \textsuperscript{0,1,2}, it appears that the O\textsuperscript{+++} and N\textsuperscript{+++} ions are at temperatures intermediate between the measured temperature for the He\textsuperscript{+} and O\textsuperscript{+++} ions.

The temperature difference between He\textsuperscript{+} and O\textsuperscript{+++} ions may be due to spatial variations in temperature. It is reasonable to assume that the purity of the gas, the electron temperature, and the ion temperature all increase toward the core of the plasma, and that the helium influx is excited and ionized in the outer regions of the plasma. An experimental test of this hypothesis would be desirable, to exclude the possibility that different ions in each small region are not in kinetic equilibrium.

The earliest divertor–limiter comparison data were taken with the helical windings energized. Although the data taken under these conditions have not been used in determining the above measure of divertor effectiveness, the results allow further characteristics of the impurity behavior to be adduced. A clean-up action in B–65 was apparent during these first runs. Light from the low stages of ionization diminished markedly in the first few days of the experiment, and continued to diminish slowly thereafter. A related electron temperature effect was observed on the O\textsuperscript{IV} intensities. During the same period, the O\textsuperscript{IV} intensity with limiter operation was observed to grow rapidly from the low value illustrated in the spectrogram of Fig. 3. Also, the limiter/divertor ratio for O\textsuperscript{IV} increased from much less than unity to greater than unity and by the time the experiments began with the helical windings not energized, the ratio reached 2 to 1.

For the low stages of ionization, the limiter/divertor ratio was about 4 to 1 after the first week of operation. This ratio decreased for each successive stage of ionization in contrast to the situation shown in Fig. 4. However, with continued operation with the helical windings energized these ratios gradually approached the situation later observed (Fig. 4) with the helical windings not energized.

From these early data it appears that the divertor action in lowering the impurity influx was somewhat greater when the machine walls had not yet been conditioned by the action of the discharge.
The ion temperatures obtained with the helical windings energized were not as high as those shown in Fig. 5 and the He\textsuperscript{II} λ4686 Å peak-to-plateau ratio was also smaller, as might be expected from the smaller scrape-off distance for this type of operation. Increased heating by use of the divertor was still observed, however.

**Confinement Time, Ionization Rate, and Divertor Effectiveness**

An empirical theory was outlined above, to relate the time behavior of the number density of He\textsuperscript{+} ions to three parameters of direct interest. We make the assumption that the intensity after the initial peak of He\textsuperscript{II} λ4686 Å is proportional to the number density of He\textsuperscript{+} ions, and plot in Fig. 6 the intensity of this radiation on a logarithmic scale vs. time for the divertor case and the limiter case. In the limiter case, the predicted plateau is readily apparent, and the peak-to-plateau ratio is approximately 3. For the divertor case, the two slopes are equally apparent, with values of 1.8 x 10\textsuperscript{-4} sec\textsuperscript{-1} and 0.25 x 10\textsuperscript{-4} sec\textsuperscript{-1}. We then obtain:

Confinement time, \( t = 200 \text{ microseconds} \)

Ionization rate of He\textsuperscript{+}, \( q = 1.4 \times 10^{4} \text{ sec}^{-1} \)

Divertor effectiveness, \( \gamma = 0.43 \).

We discuss these three parameters in turn.

**Confinement Time**—The value of 200 microseconds may be compared with the 120 microsecond confinement time obtained from the rate of pump-out for H\textsubscript{2} discharges in the baked B–1 Stellarator.\textsuperscript{9} Since the B–65 aperture has twice the area of the B–1 device, and since the magnetic fields are comparable, these two results are consistent with one another.

**Ionization Rate of He\textsuperscript{+}**—The He\textsuperscript{+} ionization rate may be compared with the ionization rates for the impurities. A crude estimate of these rates was made in the following manner. The time at which the spectral intensity for a given impurity ion reached 0.1 of its maximum was plotted vs. the logarithm of the binding energy of the last electron removed in producing that ion. The points for O\textsuperscript{+}, O\textsuperscript{++}, O\textsuperscript{+++}, C\textsuperscript{+}, C\textsuperscript{++}, C\textsuperscript{+++}, N\textsuperscript{+}, N\textsuperscript{++}, N\textsuperscript{+++}, and He\textsuperscript{+} were plotted on the same diagram. There was considerable scatter but the straight line of best fit had a slope of 1.7 x 10\textsuperscript{4} sec\textsuperscript{-1}, which is consistent with the He\textsuperscript{+} ionization rate. Using an estimated cross section\textsuperscript{4} of 3 x 10\textsuperscript{-18} cm\textsuperscript{2} for the ionization of He\textsuperscript{+} by 80 ev electrons, we infer an electron density of 1 x 10\textsuperscript{13} cm\textsuperscript{-3}. From the known starting pressure, the calculated electron density in the main discharge column is approximately an order of magnitude higher. We surmise that the ionization of the lower states occurs mostly in or near the edge of the scrape-off layer, where the electron density may be much lower.

**Divertor Effectiveness**—The value of 1/\( \gamma = 2.5 \) determined from the time variation of the singly ionized helium line agrees quite well with the impurity reduction ratio (2–3) estimated from the divertor–limiter ratios for the singly ionized impurity spectra. Furthermore, the value 2.5 for 1/\( \gamma \) appears reasonable when consideration is given to the fact that about 130 microseconds is required for a helium ion of \( kT = 50 \) ev to travel the average distance of 263 cm to the divertor and only 200 microseconds is required to diffuse out of the aperture.

**CONCLUSIONS**

We conclude that under present conditions the divertor reduces the impurity concentrations in the B–65 Stellarator by a factor of 2–3, with perhaps an even greater reduction in the core of the plasma. The use of a divertor yields an increase in the ion...
temperatures from 40 ev to 60 ev for He+ and to 130 ev for O^{4+}. The latter difference probably represents a higher temperature in the core. The effectiveness of the divertor in these experiments is apparently limited by the diffusion of plasma across the lines of force, which occurs in about the time required for a positive ion to travel around the machine. If better magnetic confinement can be achieved, and if the impurity influx is induced by ion bombardment and not photon bombardment, we may also expect considerably greater effectiveness of a divertor in reducing the impurity concentration in the discharge.

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