METHOD OF PLASMA IMPURITY
CONTROL WITHOUT MAGNETIC
DIVERTOR

BY

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PLASMA PHYSICS
LABORATORY

MASTER

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Without Magnetic Divertor

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Abstract

A method is proposed for controlling impurity generation in a tokamak by skimming and pumping the scrape-off. This method avoids many of the complications of a magnetic divertor, such as specially configured magnetic fields, toroidal symmetry, and inefficient use of toroidal field volume. Estimates are given for operating parameters. Impurity reductions of as much as a factor of 10 should be achievable. The necessary high-capacity pump would employ either titanium gettering or cryocondensation.

Method of Plasma Impurity Control

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Introduction

The advantages of divertors for controlling plasma impurities are well known. The disadvantages of divertors are chiefly the increased complexity of the coil systems and the use of expensive toroidal field volume for other than plasma volume. Since the function of a divertor is to lead the scrape-off plasma into a disposal chamber, it is of interest to study how effectively one can dispose of scrape-off plasma without the use of a specially configured magnetic field -- that is, to study whether it is practical to bring the disposal chamber to the edge of the main plasma and thereby do away with the divertor magnetic fields. With no divertor magnetic field and, therefore, no requirement for toroidal symmetry the disposal chamber could be localized, allowing it to come out between toroidal field coils. Thus, no field volume would be used up for the divertor functions. Finally, this method would eliminate any concern about destabilizing effects of divertor coils.

The main elements of the scheme are shown in Fig. 1. The device consists of a kind of inside-out limiter facing a pumping system with sufficient capacity to swallow most of the main plasma in a turn-over time (such as a large getter pump, as in PDX, or a cryopump, as in neutral injection). The reduction of recycling by the device depends on the geometry -- the obtuse angle of the neutralizer and the relatively small openings for entry of the scrape-off. Since atoms should come off the neutralizer with a roughly isotropic distribution (or perhaps even a more favorable one weighted by reflection), the geometry should

be very favorable, as long as the atoms can be captured within a few bounces. It is estimated that between one-half and three-quarters of the plasma leaving the discharge could be captured and pumped by such a device. This fraction should be large enough to make a significant reduction in impurity content.

The basic idea has been tried by Tanner¹ on the B-3 Stellarator, where, however, conditions were quite different and less favorable than present conditions. The basic idea has also been suggested by Vershkov and Mirnov² in connection with a rotating-wheel limiter.

In order to compare the method with the operation of a magnetic divertor, it is useful to review the latter here.

There are two modes in which a divertor can act to reduce plasma impurities -- the "unload" mode and the "shield" mode. In the unload mode the particles leaving the discharge are channelled into a burial chamber in order to eliminate most of the recycling and thereby to reduce charge-exchange neutral flux and, consequently, evolution of impurities from the wall and limiter. In this mode the scrape-off layer may be too thin to ionize those impurities which are evolved. In the shield mode, the scrape-off layer is made thick enough to ionize the incoming impurities so that they may be transported to the divertor chamber. The divertorless method described here operates in the unload mode and shares with the unload divertor the problem of refueling the discharge. With recycling effectively reduced, the supply of gas for continuing the discharge must come from some other source, such as some method of injection into the middle of the discharge or letting gas in at some vessel location far away from the scrape-off pumping device.

The advantages of the present scheme over wall gettering are: 1) that it is more controllable -- the openings to the vessel can be shut and the whole device can be retracted -- there need be no coating of the vessel wall or of windows; 2) that it should substantially eliminate any impurity evolution from a limiter -- whether from gas evolution or from sputtering; and 3) that it eliminates the possibility of sputtering or flaking titanium from the vessel wall (not a problem in ATC, but a potential problem in larger machines).

The key points affecting the potential usefulness of this scheme are: 1) heat concentration on the leading edges of the neutralizer plates; 2) large pumping capacity needed to accept the gas collected; and 3) scaling the device to larger machines, especially because of point (1). These points will be addressed in the estimates given below.

This idea would be relatively simple to try on PLT in the near future. It should reduce the impurity level significantly. Also, it should be useful, to some extent, to speed up discharge cleaning. It could be built in a retractable form so that it could be brought into play only when desired.

Estimates of Operation

1. Operating Parameters

The operation of our scrape-off pump, or of a divertor, is characterized by three parameters:

- 1) C_p , the plasma-capture efficiency of the device;
- 2) R_n , the fraction of all outflowing plasma which is re-cycled;
- 3) S , the shielding efficiency of the scrape-off.

The quantity C_p is determined by the geometry of the device and the scrape-off thickness, λ . The quantity λ is estimated in the usual way by $\lambda = (D_s \tau)^{1/2}$ where D_s is the perpendicular diffusion coefficient in the scrape-off, and τ is the mean time for an ion to drift around the scrape-off. Now $\tau = L/v_s$, where L is the length of an average field line going around the plasma surface until it reaches the neutralizer, and v_s is the ion sound speed. For a neutralizer which is short (in the poloidal direction) compared with a , $L = (\text{plasma surface area})/(\text{neutralizer length})$; that is, for length h , $L = 4\pi^2 aR/h$. The ion sound speed is $v_s = (AkT_{is}/m_i)^{1/2}$, where A varies with conditions, but is in the neighborhood of 4. T_{is} is the ion temperature in the scrape-off. Substituting in the expression for λ , we get $\lambda = 2\pi(D_s aR/h)^{1/2} (m_i/AkT_{is})^{1/4}$.

For a machine the size of PLT, we can make use of the estimates by Meade⁵, that is, $D_s = 2 \times 10^3 \text{ cm}^2/\text{sec}$ and $T_{is} = 500 \text{ eV}$. We have $a = 45 \text{ cm}$, $R = 132 \text{ cm}$, and take $h = 20 \text{ cm}$. The scrape-off width, then, would be $\lambda = 0.7 \text{ cm}$. Note that the scrape-off will be much wider during discharge start-up and during discharge cleaning.

We have in the usual way $n_e(x) = n_e(0)e^{-x/\lambda}$ for the electron density, where x is the distance outward from the main-plasma boundary. If we assume that the edge of the wedge-shaped neutralizer has a thickness of 1 mm, and we neglect the curvature of the edge of the plasma, then we estimate the fraction of the scrape-off landing on the edge (and therefore recycling) to be 0.13, and the capture efficiency for a 2 cm-wide slot to be $C_p = 0.82$. An additional fraction 0.05 lands outside of the slot.

The fraction, F , returning from the device has been estimated by using the vacuum system Monte-Carlo program⁶ MOLFLO.

The quantity F is dependent on the size of the box and on the sticking coefficient, f_s , on the walls. A box of reasonable size and shape (to fit between two TF coils) is shown in Fig. 2. The wall area available for pumping is approximately $15\,000\text{cm}^2$. There are two cases to be considered--those of small and of large sticking probability, f_s . The former case occurs if we employ titanium gettering and the hydrogen strikes the wall as molecules--in that case we take³ $f_s = 0.03$. The latter case corresponds to either cryo-condensation pumping, for which we take^{3, 4} $f_s = 0.27$, or to getter pumping if the hydrogen strikes the wall as atoms. In the atom case³, $f_s \geq 0.3$. (We don't really know the probability of recombination into molecules in our application, but we guess that for a few bounces, at least, the atoms are unlikely to form molecules. Thus, the higher f_s seems to be the more likely one.) For the cases of large f_s , we find $F = 0.06$. For the case of small f_s we can easily add baffles with an additional area of $11\,000\text{cm}^2$; the return fraction is then $F = 0.20$. The fraction recycled is given by R_n , where $R_n = (1 - C_p) + FC_p$. For the case of small f_s we have $R_n = 0.34$, while in the case of large f_s we have $R_n = 0.23$.

If we could use a larger port, we could increase w and decrease the angle of the neutralizer plate, which would reduce the backflow fraction F .

The shielding effect of the scrape-off should be similar to that of the outer divertors in PDX⁵; that is, we expect $S \approx 0$.

2. Impurity Reduction

Calculation of the impurity reduction expected by reducing R_n from 1.0 (simple limiter case) to 0.34 or to 0.23 (cases of our device) requires something like the transport code of Duchs, Furth, and Rutherford⁷. The case of R_n reduction from 1.0 to 0.2 has been done⁷, and it has the result that the impurity generation is reduced by at least one order of magnitude. Hence, for our case of $R_n = 0.23$, we expect a reduction of approximately 10, while for

$R_n = 0.34$ we expect a reduction of perhaps 4 or 5. This implies that, to the extent that impurities are generated during the steady phase of a discharge, the impurity content of the discharge would be reduced by a similar factor. The problem of impurity generation during the start-up phase is less well understood. The scrape-off should be much wider during this phase, which implies poor capture, C_p , and direct plasma contact with the walls. The effect of our pumping device on impurities should be much reduced, but the start-up impurity problems seem to be similar to those in a divertor machine. In the case of either impurity control device, the plasma should become cleaner as the discharge goes on and the initial plasma is buried, to be replaced by clean gas from the refueling source.

3. Refueling

Refueling is a problem⁸ for both divertor machines and our device. Simply feeding gas into the vessel to replace that swallowed by an unload device would result in charge-exchange sputtering (and other wall evolution), just as the recycling which the device reduces. This problem may be solved by pellet injection or some other method of getting hydrogen to the center of the discharge. However, for present day machines, the solution may be much simpler. If most of the impurities come in during start-up and are simply recycled along with the hydrogen, then it would be sufficient to add gas during the discharge. In this model sputtering by charge exchange neutrals is not important and the impurities are pumped out by our device along with the old gas. The added clean gas refuels the discharge. Experiments will be necessary to determine whether this method can be used, but in any case a machine with our device could be operated in a falling-density mode, just as a gettered-wall machine with no gas added during the discharge.⁹

4. Power Density on the Edge of the Device

The scrape-off density and temperature are estimated using the work of Meade.⁵ For our dimensions and for an average main-plasma density of $2 \times 10^{13} \text{ cm}^{-3}$, taking $D_p = D_s$, the density is $n_e = 1 \times 10^{12} \text{ cm}^{-3}$. The electron temperature, for $\tau_{Ee}^* = 30 \text{ msec}$ and $\tau_p = 80 \text{ msec}$ and an average temperature in the plasma of $\bar{T}_e = 1.5 \text{ keV}$, is $T_{es} = 1.0 \text{ keV}$. The power density on the leading edge of the neutralizer would be $nk(T_{es} + T_{is})v_i$, where v_i is the ion thermal velocity in the scrape-off. For the parameters used above, the power density would be $P = 5.3 \text{ kW/cm}^2$. This is very large, but bearable¹⁰ by several refractory materials. If it is necessary to have this device in contact with the plasma during runaway conditions, it will probably be necessary to have a limiter plate with a large radius of curvature and a height of a few millimeters (as indicated in Fig. 1). The disadvantage, of course, is that this plate seriously reduces the capture efficiency of the device.

5. Estimates of operation in a larger machine (TFTR)

For TFTR we take the following values: $a = 85 \text{ cm}$, $R = 250 \text{ cm}$, $T_{is} = 5 \text{ keV}$, $m_i = \text{deuteron mass}$, and for the capture device $h = 40 \text{ cm}$, $w = 20 \text{ cm}$. We assume D_s is the same as in PLT. Then using the same expression as above for λ , we obtain $\lambda = 0.65 \text{ cm}$, or practically the same as in a PLT-size machine. The device should work slightly better because of the larger value of w that is possible, as mentioned above. However, the power density at the edge is expected to be severe, primarily because of the much higher plasma temperature expected. Estimating as above, we obtain a rough value of 40 kW/cm^2 , well above what any material can withstand.¹⁰ Possible ways out of this difficulty include the following:

- 1) The power density may not be so high, because the energy loss to the wall will not have been completely eliminated,

- 2) One can use several capture devices, to spread out the heat load, and possibly devices with a greater extent in the poloidal direction,
- 3) The device can be tilted in the toroidal direction so that the power is not incident perpendicular to the edge.

6. Summary

Many of the operating parameters of the device are not well known and will have to be determined experimentally. However, the device appears capable of making a reduction of a factor of 10 in the impurity content of discharges.

Pumping

The pumping requirements are very large, naturally, since the device must swallow most of the gas filling of the machine during each particle confinement time. The gas load of PLT at an average density of $2 \times 10^{13} \text{ cm}^{-3}$ is 2 Torr-liter of molecular hydrogen. Five particle confinement times would give 10 Torr-liter of gas, or 3×10^{20} molecules. This quantity needs to be pumped in one-half second.

In connection with PDX and with large-scale neutral injection heating, there has been a great deal of study³ here of large-scale pumping systems, both getter pumping and cryopumping. For titanium getter pumping on the surface alone, we assume a capacity of one monolayer, or 6×10^{18} molecules/m². However, data³ on pumping by the volume of the titanium film indicate that the titanium can absorb 1 monolayer every 3 milliseconds, or 1.8×10^{21} molecule/m²-sec. The ultimate capacity is⁵ approximately 0.1 hydrogen molecule per titanium atom. Cryopumping has a capacity of many thousands of monolayers³. In fact, the practical limit that one runs into seems to be the safety aspect of how much hydrogen is stored in the pumping chamber.

Getter pumping on only the surface of the titanium, even with the area of 2.6m^2 , is inadequate to pump even one turn-over of hydrogen, because the wall capacity is only 1.6×10^{19} molecules. On the other hand, if we can use the volume of the titanium coating (which appears possible), then we should have the capacity to pump for our entire discharge, provided that we can evaporate the necessary ≈ 0.2 gm onto the walls before each discharge. The rate of diffusion of hydrogen into titanium is more than sufficient--the area of our pumping box could pump 5×10^{21} molecules/sec. The film thickness build-up rate for 0.2 gm/discharge over our area is only $0.02 \mu\text{m}/\text{discharge}$.

Cryopumping has plenty of capacity--i.e., 2×10^{22} molecules for our pumping box--but, of course, the walls must be warmed up to allow pumping away the hydrogen after the capacity has been reached. Our pump could accept 100-200 discharges. This limit was obtained by attempting to estimate a safe amount of hydrogen accumulation. It might be that a good design would allow a larger accumulation, in which case we could pump for many more discharges. Indications³ are that cryopumping may keep on working even when the frozen hydrogen layer is a millimeter thick!

Trial on PLT

Possible locations for the device are: 1) in a pump-line and 2) in a "manhole" port. The advantages of using a manhole are that the dimension w can be about twice as large and that the pump-lines do not have to be disturbed. The advantages of using a pump-line are that the turbomolecular pump can act as a backing pump on the device, that the manhole is left free for other diagnostic equipment, and that there are four choices of azimuthal location. If a pump-line is used, the 12-inch pipe would have to be replaced by a larger chamber to allow enough room for the high-capacity pumping system.

It would be possible, however, to mount a small version of the device in a pump-line as it is now. The smaller version would be 50 cm long and have a cylindrical pumping box 25 cm in diameter. The surface area for pumping would be $4\,000\text{ cm}^2$. In the case of gettering molecular hydrogen, $f_s = 0.03$, we would have $F = 0.36$ and the recycled fraction $R_n = 0.48$, while in the cases of large sticking probability, $f_s = 0.27$, $F = 0.20$ roughly, and $R_n = 0.34$. For the larger value of R_n , one could guess that the impurity reduction would be only a factor of 2 or 3, and for the case of the smaller R_n we have guessed (above) a reduction of 4 or 5. The pumping capacities of this smaller pump are as follows: with gettering (by the volume of the titanium film), 7×10^{20} molecules/sec, or just quickly enough¹¹ if $\tau_p = 0.1$ sec, and with cryopumping, 5×10^{21} molecules, or more than 25 shots.

As has been mentioned above, we would expect the impurity concentration to be reduced by a factor of from 2 to 10 during the steady phase of the discharge, depending on the size of pump, on when and how most of the impurities come into the discharge, and on the method of refueling.

Summary

A method is proposed for performing a divertor function perhaps less thoroughly than a magnetic divertor, but much more simply. It would require a small investment to try it on PLT. Since the device could be retracted and closed off from the torus, it need not interfere with normal operation of the machine. Its possible benefits are an effective method of impurity control, and speed-up of wall conditioning.

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11. The mass of titanium needed is the same as in the case of the larger pump-- the limitation in the present case is the rate of hydrogen diffusion.

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Fig. 1 Schematic of the device
(Top View)

Fig. 2 Example of the device with ⁷⁷³¹²⁴typical dimensions: $w=10$ cm, $h=20$ cm, $d=2$ cm, and $L=60$ cm.