Jour. Ind. Inst. Sc. 61 (B), Feb. 1979, Pp. 9–18
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Ambient boundary layer flow as a mechanism for diverting plasma impurities

R. JONES
Physics Department, University of Natal, Durban 4001, R.S.A.

Received on July 28, 1978; Revised on February 3, 1979

Abstract

A model of a toroidal plasma boundary layer is described which need not be restricted by the assumption of uniform plasma-limiter contact. Within this model a simple impurity divertor system is suggested.

Key words : Fusion, Tokamaks, plasma boundary layers.

1. Introduction

The adverse effects arising from plasma impurities (particularly high Z impurities) are well known. Impurities lead to an energy drain on the plasma *via* enhanced radiation, may influence the disruptive instability, and classically, impurities transport to the plasma center. With regard to fusion, impurities are critical. A simplified balance of the fusion alpha power generated against the bremsstrahlung radiation loss (neglecting other loss mechanisms) indicates, for example, that an impurity yielding $Z_{eff} = 4 \cdot 3$ would prevent ignition in a D–T plasma for any temperature.

Various sources of contamination have been identified : weakly bound residual gases and solids collected on the first wall from previous discharges, atoms sputtered or evaporated from the limiter and first wall during a discharge, and material liberated due to gross damage or blistering.

One suggested means of reducing impurities is the magnetic divertor scheme[1] which seeks to divert the outer field lines of the plasma from the main chamber of the system. Presumably any sputtered material would be contained in this layer, and hence the impurities are removed from the system. The divertor concept to be explored here, seeks to modify (enhance) the natural divertor effect of the parallel field plasma transport which may already be present in the boundary flow region[2] and terminate this flow at a suitably designed impurity dump. This is in contrast to the impurity flow reversal concept of Ohkawa[3] and Burrell[4] which seeks to modify (reverse) the radial transport of the impurities.

The plasma boundary-limiter shadow region contains a natural flow of plasma along field lines toward the limiter. This region may serve as a shield to absorb wall evolved impurities (for example, by sputtering or desorption) and to absorb high energy charge exchange neutrals from the hot plasma core (thus reducing sputtering). Section 2 will define some parameters relevant to the shadow region, in particular, the thickness of the flow layer. To be absorbed in this region an impurity must be ionized, and to be efficiently removed from the system (before transporting into the hot plasma) the impurity must flow with the plasma to a suitably prepared dump (*i.e.*, be collisionally pumped by the plasma). Section 3 will examine the conditions that ionization and collisional pumping impose on the flow region as well as requirements for the dump. Section 4 will consider external modification of the shadow region to enhance the flow by adding density and/or energy. Also to be discussed are ways of modifying the limiter design so as to take advantage of the natural divertor effect. Section 5 will consider implementation of this experiment on ISX.

2. Characterization of the limiter-shadow region

Ohkawa[5], Waltz and Burrell[6] have considered a model for a Tokamak boundary in uniform contact with a limiter. The limiter of a Tokamak defines a current channel and loosely defines a plasma boundary. However, plasma continues to diffuse radially past this point into the limiter-shadow region defined to be between the limiter radius and wall radius. There is no current in the shadow but the plasma may flow electrostatically along the field lines to the limiter at a speed expected to be some fraction, α, of the local sound speed,

$$c_s = (2T_e/A\,m_p)^{1/2}$$

where T_e is the electron temperature, m_p is the ion mass, and A is the ion mass number. T_e is usually greater than the ion temperature in this region. If not then T_e is replaced by the ion temperature.

The value of α will depend on collisional effects (the fast escaping electrons may be attenuated by ionizing collisions, $1 - n_0\sigma v_e t_0$ being the fraction of fast electrons still able to reach the limiter), magnetic mirroring (*e.g.*, as one enters a magnetic divertor) and the boundary conditions at the limiter (*i.e.*, electrically grounded, biased, or floated) and in the plasma (which is only approximately modelled in one dimension). Experiments in the FM–1 divertor[7] have confirmed the existence of this flow and have determined $\alpha \sim 1/3$ (limiter was electrically connected to the wall). In other experiments α has been found to be as low as 1/12.

Further evidence for a plasma flow comes from TFR[8] experiments which indicate most particle recycling on the limiter (though most of the energy went to the wall *via* radiation). In clean ATC discharges[9] most energy deposition was on the limiter *via* thermal conduction (which also indicates particle flow). T-3[10] experiments found that gas recycling from the limiter was an order of magnitude greater than recycling from an equal area of wall; however, the limiter recycling represented only 10–20% of the total particle recycling from the wall and limiter combined. Thus, there is evidence of plasma flow in the shadow, but also evidence of a relatively thick flow layer.

An estimate of the width of the flow layer may be obtained by considering the parallel flow and perpendicular diffusion. In a time t_0 an ion will flow parallel to the magnetic field a distance $l_\parallel$ and, in the same time, will transport radially a distance $l_\perp$ depending on the radial transport coefficient $D_\perp$. Hence,

$$t_0 = \frac{l_\parallel}{\alpha c_s} = \frac{l_\perp^2}{D_\perp}$$

$$l_\perp = \left(\frac{l_\parallel D_\perp}{\alpha c_s}\right)^{1/2}. \tag{1}$$

The boundary layer is known to be highly turbulent and one expects very rapid cross-field transport in this region. Whereas the more quiescent Tokamak interior has a transport which is perhaps one hundred times less than Bohm the boundary layer will probably have $D_\perp$ close to the Bohm value :

$$D_\perp \simeq D_B = T_e/16eB.$$

This assumption is widely adopted and seems to be in reasonable agreement with experiments performed in the boundary layer[15].

Then we have

$$l_\perp = 2 \times 10^{-3}\,(l_\parallel/\alpha B)^{1/2}\,(A\,T_e)^{1/4} \tag{2}$$

where MKS units are used and T_e is in eV.

Although B is several Tesla in both current and projected experiments $l_\parallel$ and T_e are less well determined. $l_\parallel$ depends critically on the particular type of limiter (or divertor) and the uniformity of contact that the plasma has with the limiter. For an ideal poloidal limiter, with uniform plasma contact, a boundary field line intersects the limiter once each transit around the torus and hence a distance $2\pi R$. However, in the shadow flow region, the plasma will tend to flow the shortest distance to the limiter which, by symmetry, indicates a null flow plane at the azimuth opposite the limiter. This reduces the distance to about $l_\parallel = \pi R$ for the ideal poloidal limiter. In practice, however, the limiter may not be ideal. In the *T*-3 device[10] which had a diaphragm-type limiter, the plasma was found to ride only on the outside edge of the limiter. Therefore $l_\parallel$ could be significantly longer. Obviously, $l_\parallel$ will depend on the programming of field coils in any real machine.

An ideal toroidal limiter will have $l_\parallel \sim \pi R q$ with q the safety factor. For a rod limiter (such as used in Doublet II) $l_\parallel$ could become even longer. In the DITE experiment[11] a field line is diverted about once every ten transits and hence $l_\parallel \sim 20\pi R$. The ideal poloidal limiter then represents a lower bound on $l_\parallel$, and in general $l_\parallel \sim C\pi R$ where $C \sim 2$ or 3 to 20.

If the limiter contact is reduced in comparison with q (*i.e.*, plasma-limiter contact length $< 2\pi rq$, with r the minor plasma radius) some field lines will (in an ideal, non-rotating plasma) never reach the limiter. Particles on these field lines will not experience any flow and will, theoretically, have to diffuse radially to the wall. Such an example is given in Fig. 1.

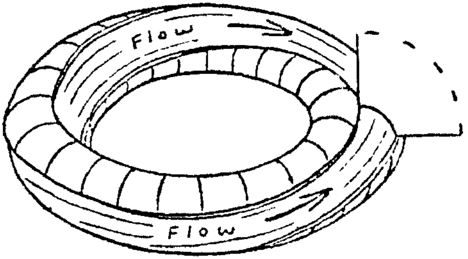

FIG. 1. Inhomogeneous plasma boundary flow. $q = 2$, limiter contact length $= \pi a/2$. Azimuthal stripes: radially thicker, stagnant band; toroidal stripes: radially thin boundary flow band.

Such a situation might arise due to poor plasma-limiter contact or if one reduces the limiter size (contact) intentionally in order to increase $l_\perp$. (We will see later why one would want to increase $l_\perp$ in some machines.) In reality, of course, shear and poloidal $\mathbf{E} \times \mathbf{B}$ driven plasma rotation will act to reduce this effect, as will microinstabilities, localizing its maximum impact to toroidal and azimuthal positions nearest to the limiter-plasma contact points. Still, significant variations in boundary layer thickness may be produced and our estimates of $l_\perp$ must be taken as averages. This phenomenon should be explored experimentally and may have impact on such things as RF coupling to the plasma boundary.

The flow thickness (averaged), $l_\perp$, is only weakly dependent on T_e and not at all on density; however, it will be useful to know the values of n and T_e in the shadow region. Unfortunately, there is little consistent experimental data on this region. Extrapolation of measurements on T-3[10], TFR[8] and ATC[9] indicate density $\sim 10^{17}$ to 10^{19} m^{-3} and $T_e \sim 1$ to 100 eV. This indicates the need for specific shadow region measurements. Recent PLT[12] values are $T_e = 5$ eV and $n_e = 10^{18}$ m^{-3}.

We can now estimate a value of $l_\perp$. Assuming $l_\parallel = \pi R$ with $R = 4$ m, $B = 3T$, $a = 1/3$, $A = 1$, and $T_e = 10$ eV, then $l_\perp \sim 1\ 1/3$ cm. If $l_\parallel$ were, in fact, about 10 times longer (which can certainly be achieved on DITE), then $l_\perp \sim 4$ cm. A smaller value of α can probably also be achieved.

Certainly the shadow gap, l_g, must be greater than $l_\perp$ to insure particle recycling on the limiter. The long path length ($l_\parallel$) in T-3 (due to plasma contact only on a small section of limiter) may have increased $l_\perp$ enough to account for the wall recycling observed.

3. Boundary layer conditions for impurity pumping

Having characterized the boundary layer, we must now determine whether conditions there are suitable for naturally removing impurities. Three essential requirements are that the flow layer ionize the impurities, collisionally pump them to the limiter (or dumping mechanism), and that the impurity dump prevent re-entry of the impurities into the system. The ionization mean free path is given by

$$\lambda = V_0/(n\,\langle\sigma v\rangle_{\text{ionize}})$$

where n is the local plasma density, V_0 the impurity entry speed, and $\langle\sigma v\rangle_{\text{ionize}}$ the electron-impurity ionization rate coefficient. To insure ionization of the impurities in the flow layer, it is necessary that $l_\perp > \lambda$, *i.e.*,

$$nl_\perp > V_0/\langle\sigma v\rangle_{\text{ionize}}. \tag{3}$$

Sputtered impurities have an energy of the order of a few eV[13] leading to $V_0 \sim$ few times 10^3 m/sec for impurities. For hydrogen at 10 eV, ($V_0 \sim 10^4$ m/sec), $\langle\sigma v\rangle \sim 2 \times 10^{-14}$ m^3/sec[14] and with $l_\perp \sim 0{\cdot}05$ m then we need $n > 10^{19}$ m^{-3}. Alternatively, if $n = 10^{18}$ m^{-3} then we need $l_\perp > 0{\cdot}5$ m. Higher mass number impurities relax this condition somewhat to $n > 10^{18}$ m^{-3} but even then the condition is only marginally satisfied in the shadow region. Certainly increasing $l_\perp$ would relax the ionization condition but there may be other limiting criteria. l_g must be increased too which may lead to MHD stability problems. Artificially increasing the density will be discussed in Section 4.

Once ionized, the impurities will flow along the field in the boundary, but it is desired that they reach the limiter before cross-field diffusion carries them into the hot plasma. Hence it is necessary that they flow in the same direction as the plasma so as to achieve the shortest path length to the limiter. This places restrictions on the frequency of collisions made by impurities with the plasma.

We tacitly assume a collisional boundary with regard to the parallel motion, and it is of interest to examine the collision lengths for electrons, ions and impurities. These are

$$\lambda_e \sim \lambda_i \sim 1{\cdot}4 \times 10^{13}\, T_e^2/nL$$

$$\lambda_I \sim 10^{13}\, A^{1/2}\, T_i^{3/2}\, T_I^{1/2}/(Z^2\, nL)$$

where L is the Coulomb Logarithm and Z is the impurity charge. With $n = 10^{18}\, m^{-3}$, $T = 10$ eV and $L = 13$ then $\lambda_e \sim \lambda_i \sim l$ meter and $\lambda_I \sim 3/4\, A^{1/2}/Z^2 \sim 1$ meter for $Z = 1$. Since $l_\parallel$ is many meters collisionality seems a good assumption. Although the boundary temperature is low there may be significant second and third ionization of impurities, hence leading to $\lambda_I \sim$ few cm.

The steady state force balance equation for the impurities colliding with ions is, in one dimension:

$$0 = -\frac{Kn_I T_I}{\delta} - \nu_{Ii} n_I m_I (sV_I - V_i)$$

where ν_{Ii} is the impurity-ion collision frequency, δ is the pressure gradient scale length, s denotes the sign of the impurity velocity, V_I, and K is the sign of the pressure gradient. If $s > 0$,

or

$$\nu_{Ii} > \frac{KT_I e}{m_I V_i \delta}$$

(where T_I is now in eV) then impurities will be " collisionally pumped " by the interaction with the plasma flow. This pumping action will drive the impurities under the limiter and into the neutral gas pumping region. It will also serve to prevent backstreaming from the vacuum pumps.

If

$$T_I \sim T_i, \quad m_I \sim Am_p, \quad K = 1, \quad \delta = l_\parallel/2, \quad V_i = \alpha c_s$$

then

$$\nu_{Ii} > \frac{2T_i e}{Am_p \alpha c_s l_\parallel} \tag{4}$$

using

$$\nu_{Ii} = 2 \times 10^{-12}\, n_i Z^2/(AT_i^{3/2})$$

yields

$$n_i l_\parallel > 10^{16}\, T_i^{5/2}/(T_e^{1/2}\, Z^2\, \alpha) \tag{5}$$

for $T = 10$ eV, $Z = 1$, $\alpha = 1/3$, and $l_\parallel = 10$ meters:

$$n_i > 3 \times 10^{17}\, m^{-3}.$$

This condition is only slightly different from the condition on density imposed before, although the ionization condition is ultimately the more restrictive one.

Finally, the limiter itself must be modified. If the impurities merely strike and bounce off they may be injected into the plasma. Furthermore, they may sputter new impurities.

4. Modifications in the boundary region

As was seen in the previous section, the natural divertor appears to be marginal. Although the effect probably occurs to some extent in present Tokamaks, no attempt is made to take advantage of or augment the impurity pumping. The pumping ducts are not even located near the limiter in most machines. (Of course this is not true for magnetic divertor Tokamaks where the limiter is the neutralizer plate and certainly is differentially pumped.) For a Tokamak with magnetic divertor one may want to increase $l_\perp$ by removing one or more of the neutralizer plates so as to increase $l_\parallel$.

The external addition of density to the limiter shadow would be particularly complex. Ideally, plasma (or gas and energy) would be introduced at the limiter radius and would not transport into the central plasma. The creation of a density peak in the shadow region would be particularly advantageous in holding the impurities in the flow region. In Princeton's TFTR it is hoped to create inverted profiles transiently in order to extract impurities.

If the application of RF power with gas injection still upsets the overall energy balance then simple enhancement of the existing boundary layer may only occur transiently. Of course, if sufficient gap space is available, $l_g >$ several $l_\perp$, there is another way to create a dense shielding plasma. Well beyond the existing flow layer the " vacuum " region can be filled by an externally injected plasma of thickness $\sim 2l_\perp$ and arbitrary density. Again, with l_g large this external shell will exist nearly independent of the interior plasma and natural boundary. Both flows will then exhaust to a magnetic divertor or other suitable impurity dump (see the discussion of the " capped limiter " to follow).

The power required to ionize injected gas can be estimated from

$$P = 3/2\, nT\, (l_g)\, (2\pi a)\, (2\pi R)\, \alpha c_s / l_\parallel .$$

For $n = 10^{18}\ \mathrm{m}^{-3}$, $T = 10\ \mathrm{eV}$, $l_g = 20\ \mathrm{cm}$, $a = 1\ \mathrm{m}$, $R = 3\ \mathrm{m}$, $l_\parallel \cong 100\ \mathrm{m}$, $\alpha \lesssim 1/3$ we get $P \approx 5$ kWatts.

Since about 90% of the boundary energy in Tokamaks is lost to recombination radiation, etc., we would probably need closer to 50 kilowatts in practice. Still, this could easily be provided, and the requirement does not depend strongly on machine size since we are creating only a thin, cold plasma shell. (A cold dense shell might produce only low energy charge exchange neutrals which would be unable to sputter the wall materials.)

As we have mentioned several times, the design of the limiter-impurity dump is very important since the contaminants must physically be removed from the system. A magnetic divertor may be desired but requires substantial energy and tampering with the confining field configuration.

Whereas the magnetic divertor removes the limiter to a remote, differentially pumped chamber it is also possible to bring differential pumping to the limiter and leave the field configuration unchanged. One way to attack this problem is to employ a "capped" of "T" shaped limiter such as that shown in Fig. 2. The cap assumed is to be larger

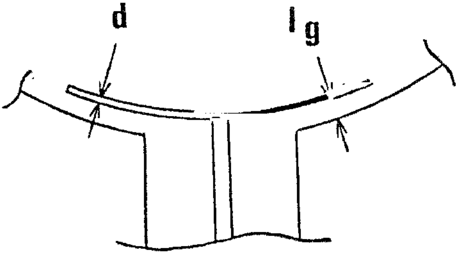

FIG. 2. Capped limiter and neutralizer plate/support located over the pumping duct.

than the duct which pumps it and located close to the wall. The ionization length for impurities should be smaller than the cap radius to prevent neutral impurities from escaping the pumping region. (And, of course, vacuum pumping must be adequate to remove the neutral buildup.) This restriction gives a limiter diameter of perhaps one meter. Such a size is, in fact, smaller than the limiter area needed for adequate cooling in reactor-scale Tokamaks. Condition 5 assures that pumping will also take place under the limiter.

Gettering the neutralizer plate has been suggested but may be ineffective at high operating temperatures. Contouring the neutralizer plate to reflect the neutrals toward the duct may also be of some value.

Since the object of the capped limiter would be to locally remove the flow layer the usual plasma-limiter particle recycling would be reduced. This is observed in the DITE device, and necessitates the addition of new (clean) gas by external means. Of course gas will find it hard to enter through the shielding layer, hence refueling would be through a hole in the limiter. At first sight we may expect that the total vacuum pumping requirements have been increased. However, virtually all of the gas is returned (as plasma, flowing fast) to, and under the limiter. For this reason no impedance is seen by the pumps during a discharge. (Pump down in air will be inhibited of course.)

The edge of the limiter cap will necessarily intercept part of the flow layer. This thickness must be as cool and small as possible, relative to $l_\perp$, to reduce sputtering and yet thick enough to withstand the thermal load. If cooling is effective between discharges, then thermal diffusion is the limiting parameter. Heat deposited on the plate can diffuse, in time t_g, to a depth :

$$d = (D_{\mathrm{th}} t_d)^{1/2}$$

where

$$D_{th} = K/(\rho C_p)$$

with K the thermal conductivity of the material, ρ its density, and C_p the specific heat at constant pressure. For tungsten or molybdenum, $D_{th} = 0 \cdot 5$ cm^2/sec and hence for a discharge of less than a second duration a cap about 0·5 cm thick is probably adequate anyway.

The fraction of the flow intercepted by the edge is $f \sim 2d/l_\perp$ or, with $l_\perp \sim 3$ cm, $f \sim 1/3$. Perhaps half this would re-enter the plasma. Hopefully, if we can create an external shielding plasma impurities would ionize far out and all pass under the cap. One can then hope to make and cool the edge so that it will inject relatively little contamination.

5. Implementation and testing on ISX

A project to test these ideas seems ideally matched to the objectives outlined for the Impurity Study Experiment (ISX) of General Atomic Co. and Oak Ridge National Laboratory. A satisfactory experimental test of the divertor action, however, may be difficult on a relatively small, low density Tokamak. Assuming a limiter shadow characterized by $n = 10^{18}\,\mathrm{m}^{-3}$ and $T = 10$ eV and toroidal limiter and $q = 4$ then $l_\parallel = 11$ m and $l_\perp = 0 \cdot 015$ m. The impurity pumping condition is satisfied (eqn. 5) but the ionization condition is not. Two approaches to an experiment can be suggested: 1. We can inject a preionized impurity and study the subsequent divertor action. 2. Restrict the studies to the injection of slow, readily ionizable tracers.

A problem common to all small scale experiments is that the important plasma parameters, density, temperature, and size, are all scaled down from reactor values while the impurity reflux characteristics, velocity and ionization rate, remain almost unchanged. A measured puff of room temperature Argon or Xenon tracer might help to restore the scaling since the impurity influx velocity would be reduced. In this case, $nl_\perp > 10^{16}\,\mathrm{m}^{-2}$. We might also seek to replace the ISX limiter to modify $l_\perp$. To study the removal as well as pumping we would have to instal a capped limiter.

6. Acknowledgement

The present work was carried out in cooperation with Dr. Bill McHarg of the General Atomic Company and at the suggestion of Dr. Tihiro Ohkawa. Contributions from the " coil-less divertor " and " shielding divertor " ideas of Ohkawa and Meade are acknowledged.

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