JAERI-M
8390

# "WALL LAPPING PLASMA" WITH ROTATING HELICAL RESONANT ISLANDS FOR IMPURITY CONTROL AND MECHANICAL VALVES FOR ASH EXHAUST IN A REACTOR-GRADE TOKAMAK WITHOUT A DIVERTOR

September 1979

Teruhiko TAZIMA and Masayoshi SUGIHARA

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

JAERI-M 8390

# "WALL LAPPING PLASMA" WITH ROTATING HELICAL RESONANT ISLANDS FOR IMPURITY CONTROL AND MECHANICAL VALVES FOR ASH EXHAUST IN A REACTOR-GRADE TOKAMAK WITHOUT A DIVERTOR

Teruhiko TAZIMA and Masayoshi SUGIHARA

Division of Large Tokamak Development
Tokai Research Establishment, JAERI

(Received August 28, 1979)

An alternative conception of the divertor, called "Wall Lapping Plasma" is proposed for impurity control and ash exhaust which are one of the most serious problems in reactor-grade tokamaks. Resonant helical islands formed in the boundary region rotate when we add rotating helical field by two sets of external helical coils whose current changes alternately. Consequently the plasma surface in contact with the wall by the islands rotates along the whole wall surface, so that the plasma contamination by evaporation of wall surfaces due to local heat deposition can be avoided.

Plasma particles flow along the magnetic force lines intersecting the wall by islands. Intersecting angle is very small, so that mechanical valves with small height of opening located on the wall can exhaust ash easily, since backflow of neutralized helium is small because of the narrow opening.

The necessary helical field is only 1/500 of the toroidal magnetic field, the total valve area is less than several percent of the wall surface area: besides the valves are easily repairable. "Wall Lapping Plasma" will be interesting as an alternative of the divertor because of the simple technology.

Keywords: Tokamak, Impurity Control, Ash Exhaust, Resonant Islands, Plasma Rotation, First Wall

# ダイバータなしトカマク炉において，不純物制御用の回転ヘリカル共鳴磁気島および灰除去用機械的バルブを備えた“壁面擢動プラズマ”

日本原子力研究所東海研究所大型トカマク開発部
田島　輝彦・杉原　正芳

（1979年8月28日受理）

ダイバータに替わる新概念として，トカマク炉における最も困難な問題の一つである不純物制御および灰除去を解決する“壁面擢動プラズマ”を提案する。外部ヘリカルコイルによってプラズマ境界に形成される共鳴磁気島は，2セット用意されるこのヘリカルコイルに交番電流を流すことにより回転する。

すなわち，この磁気島により，壁に接するプラズマ境界は全壁面を擢動することとなり，局所加熱による壁面蒸発に伴う不純物混入が防止される。プラズマ粒子は，磁気島によって壁に鎖交する磁力線に乗って流れる。壁に鎖交する角度が非常に小さいため，壁面に設置された機械的バルブは，その小さい開口部高さで粒子を取り込むことができ，また取り込まれて中性化した粒子の開口部からの逆流も小さくでき，灰除去が容易に行える。

必要ヘリカル磁場はトロイダル磁場の1／500程度で良く，また設置されるバルブ面積も壁表面の数％以内で充分であり，このバイブは修理交換が容易である。“壁面擢動プラズマ”は，その技術的容易さから，タイバータに替わる概念として魅力的と考える。

# CONTENTS

# 目　　　　次

## 1. INTRODUCTION

Impurity control and ash exhaust are one of the most serious problems in a reactor-grade tokamak. A divertor is anticipated to provide a viable methods for impurity control and ash exhaust. However the usual divertor conceptions will cause serious technological difficulties in future large DT machines. A poloidal divertor with interior coils (i.e. whose coils are located inside the toroidal field coils), like ones employed in DIVA, T-12, PDX, ASDEX and JT-60, seems unrealistic for the large DT machines considering automatic assembly and de-assembly of the coils. When we employ an elongated plasma and SC poloidal coils, a poloidal divertor with exterior coils and small power consumption can be imagined [1]. However, it still has a difficult technological problem, i.e. the automatic assembly and de-assembly of the divertor plates. We should note that the interior coils are essential for a circular plasma as in JT-60 [2].

On the other hand, a bundle divertor is more preferable than the poloidal divertor from the technological viewpoint, although it needs large power consumption and can not be employed in a machine with a high toroidal field because of its high magnetic strength. However, the bundle divertor gives a large ripple of the toroidal field which will cause a serious energy loss by ripple diffusion as theoretically predicted.

At present, we have no perfectly reliable method from both physical and technological view points for impurity control and ash exhaust even in a machine with the divertor. We propose a following new conception called "Wall Lapping Plasma" with rotating helical resonant islands for impurity control and mechanical valves for ash exhaust in a reactor-grade tokamak without the divertor.

Resonant islands are formed at the rational surface when we add a small helical field (e.g. 1 - 2% of the poloidal field) by external helical coils (Fig. 1). This configuration is used for a divertor called "Resonant Helical Divertor" proposed by F. Karger and K. Lackner [3]. Helical divertor plates and helical shielding plates are installed inside the islands in this divertor. However, it seems complicated structure to install these helical plates inside the vacuum chamber, and it also seems dangerous that the heat load to the edge of the shielding plates will amount to over several kW/cm$^2$ which may cause severe evaporation, since besides the primary islands, islands of higher mode numbers are formed on the corresponding surfaces owing to the toroidal curvature and setting errors of poloidal and toroidal coils, so that these islands may overlap and the field lines are ergodized [4].

More simple structure avoiding extremely large heat deposition can be imagined as follows. In order to rotate these islands, two sets of helical coils are located and each current is changed alternately at 1∿10 Hz. Consequently, the plasma surface contacting with the wall rotates along the whole wall surface. Therefore, we can avoid the evaporation of the first wall by local heat deposition. Ergodization of the field lines can help above effect, since high heat conduction flows along the primary islands will be decreased.

As to the ash exhaust, simple pumping through ports adjacent to the plasma periphery seems very difficult, since machine structures limit the pumping conductance to a level at which equilibrium can be achieved only at high ash pressure at the periphery. We employ simple mechanical valves located on the first wall for the ash exhaust (Fig. 2). Plasma and helium ions flow into the narrow valve openings along the magnetic force lines and only a small fraction of these particles can backflow to the bulk plasma (Fig. 3). The most important point to design these valves is what a kind of shape is preferable to avoid evaporation by local heat deposition on valve edges as described in section 3.

The other difficult problem in this system is a countermeasure to the plasma contamination by the first wall material due to sputtering by plasma particles and self sputtering by impurity ions. The low Z first wall with low chemical sputtering yield is preferable except the case where most of the energy losses carried by particles from the bulk plasma (i.e. conduction and convection losses) is converted into radiation in the boundary region and consequently the edge temperature is cooled down to 50∿100 eV, or the case where the boundary temperature is reduced by high electron heat conduction along the field lines to the wall.

In the following sections, we discuss our new conception in the case of TNS such as INTOR whose major parameters are

| | | |
|---|---|---|
| Major Radius | R | 5 m |
| Minor Radius | a/b | 1.2/1.8 m |

| | | |
|---|---|---|
| Plasma Volume | $V$ | $200\ m^3$ |
| Plasma Surface | $A$ | $300\ m^2$ |
| Toroidal Field | $B_z$ | 5 T |
| Plasma Current | $I_p$ | 4.75 MA |
| Fusion Output | $P_f$ | 450 MW |
| α-particle Output | $P_\alpha$ | 90 MW |
| Average Ion Density<br>$(\bar{n}=\bar{n}_D+\bar{n}_T,\ \bar{n}_D=\bar{n}_T)$ | $\bar{n}$ | $1.2\times 10^{20}\ p/m^3$ |
| Average Temperature<br>$(\bar{T}=\bar{T}_e=\bar{T}_i)$ | $\bar{T}$ | 10 keV |
| Burn Time | $\tau_B$ | 200 S |

## 2. HELICAL RESONANT ISLANDS FOR IMPURITY CONTROL

### 2.1 Width of Manetic Island by Externally Applied Helical Field [5]

In order to evaluate the necessary helical field, we roughly estimate the width of magnetic islands formed by externally applied helical field. The magnetic field of tokamaks with helical windings in a cylindrical co-ordinate system (r, θ, z) can be written as

$$\vec{B} = B_z[\ \vec{e}_z + \frac{r}{R\ q(r)}\ \vec{e}_\theta + \vec{\nabla}\tilde{\phi}_h \sin\zeta\ ]\ , \qquad (1)$$

where

$$\zeta = m\theta - \frac{nz}{R}\ .$$

$\tilde{\phi}_h$ is a scalar potential for the helical field normalized by longitudinal field $B_z$. R and q(r) are major radius and safety factor, respectively, and m and n are poloidal and toroidal mode number. For $nr/mR \ll 1$, Eq. (1) is rewritten as

$$\vec{B} = B_z[\ \vec{e}_h + \vec{e}_h \times \vec{\nabla}\psi(r,\ \zeta)\ ]\ , \qquad (2)$$

where

$$\vec{e}_h = \vec{e}_z + \frac{nr}{mR}\ \vec{e}_\theta\ ,$$

| | | |
|---|---|---|
| Plasma Volume | $V$ | $200\ m^3$ |
| Plasma Surface | $A$ | $300\ m^2$ |
| Toroidal Field | $B_z$ | 5 T |
| Plasma Current | $I_p$ | 4.75 MA |
| Fusion Output | $P_f$ | 450 MW |
| α-particle Output | $P_\alpha$ | 90 MW |
| Average Ion Density<br>$(\overline{n}=\overline{n}_D+\overline{n}_T,\ \overline{n}_D=\overline{n}_T)$ | $\overline{n}$ | $1.2\times 10^{20}\ p/m^3$ |
| Average Temperature<br>$(\overline{T}=\overline{T}_e=\overline{T}_i)$ | $\overline{T}$ | 10 keV |
| Burn Time | $\tau_B$ | 200 S |

## 2. HELICAL RESONANT ISLANDS FOR IMPURITY CONTROL

### 2.1 Width of Manetic Island by Externally Applied Helical Field [5]

In order to evaluate the necessary helical field, we roughly estimate the width of magnetic islands formed by externally applied helical field. The magnetic field of tokamaks with helical windings in a cylindrical co-ordinate system (r, θ, z) can be written as

$$\vec{B} = B_z[\ \vec{e}_z + \frac{r}{R\ q(r)}\ \vec{e}_\theta + \vec{\nabla}\tilde{\phi}_h \sin\zeta\ ]\ , \tag{1}$$

where

$$\zeta = m\theta - \frac{nz}{R}\ .$$

$\tilde{\phi}_h$ is a scalar potential for the helical field normalized by longitudinal field $B_z$. R and q(r) are major radius and safety factor, respectively, and m and n are poloidal and toroidal mode number. For $nr/mR \ll 1$, Eq. (1) is rewritten as

$$\vec{B} = B_z[\ \vec{e}_h + \vec{e}_h \times \vec{\nabla}\psi(r,\ \zeta)\ ]\ , \tag{2}$$

where

$$\vec{e}_h = \vec{e}_z + \frac{nr}{mR}\ \vec{e}_\theta\ ,$$

$$\psi(r,\ \zeta) = \psi_0(r) + \frac{r}{m}\,\tilde{b}_r(r)\ \cos\zeta \quad ,$$

$$\psi_0(r) = \int dr\Big[\ \frac{r}{R\,q(r)} - \frac{nr}{mR}\ \Big] \quad ,$$

$$\tilde{b}_r(r) = \frac{\partial\tilde{\phi}_h}{\partial r} \quad .$$

In the above expression, $b_r$ is radial component of the magnetic field by helical windings and $\psi(r,\ \zeta) = \mathrm{const.}$ represents magnetic surfaces. To obtain the island width, we expand $\psi(r,\ \zeta)$ near the resonance surface $q(r_s) = m/n$

$$\psi = \frac{1}{2}\ \psi''_{0s}\ x^2 + \frac{r_s}{m}\ \tilde{b}_{rs}\ \cos\ \zeta \quad , \tag{3}$$

where

$$x = r - r_s \quad .$$

Rewriting Eq. (3), we obtain

$$x^2 = \Delta^2[\ k^2 - \sin^2\frac{\zeta}{2}\ ] \quad , \tag{4}$$

$$\Delta^2 = \frac{4r_s}{m}\left|\frac{\tilde{b}_{rs}}{\psi''_{0s}}\right| = \frac{4R}{n}\ \frac{q(r_s)}{q'(r_s)}\left|\ \tilde{b}_{rs}\right| \quad . \tag{5}$$

Here $\Delta$ represents a half width of the magnetic island. This result agrees with the expression obtained by Matsuda, Yoshikawa [6] except for a numerical factor. For INTOR plasma, $\Delta \sim 20$ cm when $\tilde{b}_{rs} \sim 1/500$ (i.e. $b_{rs} \sim 100$ Gauss). Thus, considerably large helical islands can be formed by the resonant helical field with relatively small amplitude but fairly high coherency. Arbitrary error field may contain the resonant component, so that this error field can also form magnetic islands. However, since arbitrary error field with high coherency may not be expected, total amplitude of the error field will become so large that the performance of the plasma will be deteriorated.

## 2.2 Helical Coils

Let us estimate the helical coil current required for this island formation. We employ $q = 3$ resonance. Then, three pairs of helical coils are needed. In a straight cylinder case, scalar potential $\phi_h$ by n-pairs helical winding coils is given as [7]

$$\phi_h = \frac{2\mu_0 J\alpha n r_0}{\pi} \sum_{p=0}^{\infty} K_N' \,(N\alpha r_0) I_N(N\alpha r) \quad , \tag{6}$$

$$N = (2p+1)n$$

where $\alpha = 2\pi/\ell$, $\ell$ is the pitch of the helical winding. Helical coils are set on a cylinder of radius $r_0$. $I_N$ and $K_N$ are the modified Bessel functions. Based on Eq. (6), we evaluate the required current J to produce about 100 Gauss near the $q = 3$ resonance surface.

We assume $q(r) = 3$ surface is located at the plasma edge surface. For INTOR plasma, $a = 1.2$ m. Since $q = 3$ and $n = 3$, $N = 3$ $(m = 3,\ n = 1)$ is the fundamental component of the helical field and $N = 9$ $(m = 9,\ n = 3)$ is the second harmonics. We assume INTOR size plasma and $r_0 = 2$ m. From Eq. (6), we can evaluate that $J = 40 \sim 50$ kA is sufficient for the radial component $b_r$ by only fundamental component of $\phi_h$ to be 100 Gauss at the $q = 3$ surface. It can also be shown that the fundamental component of the helical magnetic field falls by $(r/a)^{m-1}$, so that inner hot plasma will not be affected by this helical field. Figure 4 shows this feature. The amplitude of the second harmonics is also shown in the figure. It is smaller than the fundamental one by an order of magnitude. The case of $q = 2$ resonance is also shown as a reference. In this case, too, $J \sim 40$ kA is shown to be sufficient.

When we employ two sets of helical coils whose currents are altered periodically and consequently the phase between each coil proceeds in poloidal direction, magnetic islands will rotate. In addition to this rotation, appropriate destruction of island will make the plasma contact with the first wall almost uniformly.

## 2.3 Destruction of Magnetic Island

It is well known that the magnetic island is easily destroyed and magnetic field lines become ergodized by various magnetic perturbations

[8][9]. Among them are toroidal field ripple and the effect of toroidicity [10][11]. Primary islands by external helical windings are shown to be destroyed by the coupling between a helical field and toroidal curvature [4].

These destruction of magnetic islands and ergodization of the field lines are favorable for the heat load on the first wall and exhausting valves. Numerical calculations on the degree of destruction of the primary island and the extent of ergodic region are now under way.

Let us now estimate the particle diffusion in islands and ergodized magnetic region. We assume that particle motion is random walk, of which step length is the primary island width $\Delta$ and time step $\Delta t$ is that required for the particle to move along the island to the opposite side. Then, the diffusion coefficient is approximately given by

$$D \sim \frac{\Delta^2}{\Delta t} \quad . \tag{7}$$

The step $\Delta t$ can be estimated as follows [5]. From Eq. (4), total length L of the field line in z direction when it circulates the island is

$$L = \oint dz = \oint \frac{B_z}{mB_\theta - \frac{nr}{R}B_z} r d\zeta \sim \frac{r_s}{m\psi_0''} \oint \frac{d\zeta}{x} = \frac{r_s}{m\psi_0''\Delta} \oint \frac{d\zeta}{\sqrt{k^2 - \sin^2(\zeta/2)}}$$

$$L = \begin{cases} L_0 \dfrac{2}{\pi} \dfrac{K(1/k)}{k} & \text{for } k > 1 \\ L_0 \dfrac{2}{\pi} K(k) & \text{for } k < 1 \quad , \end{cases} \tag{8}$$

where

$$L_0 = \frac{2\pi r_s}{m\psi_0''\Delta} = \frac{2\pi qR}{m} \Big/ \frac{1}{q}\frac{dq}{dr}\Delta \quad . \tag{9}$$

As a reference, in a vacuum region, $q = (\frac{r}{a})^2 q_a$, so that

$$L_0 = \frac{2\pi qR}{m}\frac{r_s}{2\Delta} \quad .$$

For INTOR plasma, $L_0 \sim 94$ m. The ratio $L/L_0$ is shown in Fig. 5 [1]. When $k = 1$ (separatrix line), L becomes infinity. Well inside the separatrix line, $L \sim L_0$. In this case, $\Delta t \sim L_0/v_s$ ($v_s$: sound velocity), and D is evaluated as $D = 10 \sim 20\ m^2/s$ for INTOR plasma. This value of diffusion coefficient seems to be fairly large. When the magnetic field line forming the island intersects the first wall, particles on the field line will be lost into the first wall fairly fast. In this case, recycling of particles becomes very large. However, near the separatrix line, since L becomes large, it will take quite a long time for the particles to move along the field line across the island width. Thus, the global particle diffusion should be determined by the diffusion in stochastic magnetic field near the separatrix line [12]. Consequently, the particle recycling in the boundary region might be by several times enhanced due to externally applied helical field.

## 3. MECHANICAL VALVE FOR ASH EXHAUST

### 3.1 Valves

In order to operate a burning plasma for a long time under the critical beta, ash exhaust is necessary to prevent the density excess. Recycling flow of particles near the plasma boundary can be expected to be larger than that in the bulk plasma by $10 \sim 20$ times, so that it is sufficient to exhaust $5 \sim 10\%$ of the recycling helium through the exhausting ports. By simple opening ports, of which area is $5 \sim 10\%$ of total area of vacuum vessel, we cannot expect to exhaust the same percents of recycling particles, since only small portion of recycling particles, which enter into the openings by chance, is exhausted. Therefore, we must install a sort of valve in front of the opening ports to guide $5 \sim 10\%$ of recycling particles into the ports.

This valve must meet the following requirements.

(1) Collect $5 \sim 10\%$ of recycling particles.
(2) Bear large heat load.
(3) Easy to maintain or repair.

Similar valve for impurity control has been proposed by J. F. Shivell [13]. However, the valve of Ref. [13] cannot bear high heat load in reactor-grade tokamaks. An example of the valve, which can meet these requirements, is shown in Fig. 2. In the following, we examine each and D is evaluated as $D = 10 \sim 20\ \mathrm{m}^2/\mathrm{s}$ for INTOR plasma. This value of diffusion coefficient seems to be fairly large. When the magnetic field line forming the island intersects the first wall, particles on the field line will be lost into the first wall fairly fast. In this case, recycling of particles becomes very large. However, near the separatrix line, since L becomes large, it will take quite a long time for the particles to move along the field line across the island width. Thus, the global particle diffusion should be determined by the diffusion in stochastic magnetic field near the separatrix line [12]. Consequently, the particle recycling in the boundary region might be by several times enhanced due to externally applied helical field.

## 3. MECHANICAL VALVE FOR ASH EXHAUST

### 3.1 Valves

In order to operate a burning plasma for a long time under the critical beta, ash exhaust is necessary to prevent the density excess. Recycling flow of particles near the plasma boundary can be expected to be larger than that in the bulk plasma by 10∿20 times, so that it is sufficient to exhaust 5∿10% of the recycling helium through the exhausting ports. By simple opening ports, of which area is 5∿10% of total area of vacuum vessel, we cannot expect to exhaust the same percents of recycling particles, since only small portion of recycling particles, which enter into the openings by chance, is exhausted. Therefore, we must install a sort of valve in front of the opening ports to guide 5∿10% of recycling particles into the ports.

This valve must meet the following requirements.

(1) Collect 5∿10% of recycling particles.
(2) Bear large heat load.
(3) Easy to maintain or repair.

Similar valve for impurity control has been proposed by J. F. Shivell [13]. However, the valve of Ref. [13] cannot bear high heat load in reactor-grade tokamaks. An example of the valve, which can meet these requirements, is shown in Fig. 2. In the following, we examine each requirement in detail.

(1) The valves stick out into the plasma to guide the recycling particles into the exhausting ports. Since $B_r$ is much smaller than $B_z$, the shadow area of the valve is $B_z/B_r$ times larger than that of the valve itself. For INTOR plasma, $B_z/B_r \sim 500$ and $A_w$ (first wall surface area) $\sim 300\ m^2$. Thus, about 20 valves, of which opening height is about 1 cm and opening area is 0.5 $m^2$, are shown to be sufficient to collect $5 \sim 10\%$ of recycling particles.

(2) Since the plasma contacts with whole wall surface almost uniformly by means of rotating the helical resonant islands, heat load of the first wall can be suppressed well below to bearable level for evaporation (at most 30 $W/cm^2$ for INTOR plasma). However, when the valves are put perpendicularly to magnetic field lines, the heat load on the front edges are expected to be quite large. Let us estimate the heat flux w along the magnetic field lines.

In wall lapping plasma, the magnetic field line intersects with the first wall by radial component of the field line $B_r$. Thus, when the total heat flowing from the main plasma $P_\alpha$ is sustained uniformly by all of the first wall with the area $A_W$,

$$w\, A_W \frac{B_r}{B_z} = P_\alpha \quad ,$$

For INTOR plasma, $B_r/B_z \sim 1/500$, $A_W \sim 300\ m^2$ and $P_\alpha \sim 90$ MW so that $w \sim 15\ kW/cm^2$. The edge of the valve perpendicular to the field line will suffer this heat load, which will cause serious evapolation. In order to mitigate the heat load to the edge, the valve is bent down slightly as shown in Fig. 2. As a result, the front edge does not suffer heat load directly. The heat load on the front surfaces of the valves is naturally equal to that on the first wall, i.e. under 30 $w/cm^2$, while that on the inner back surfaces, onto which guided particles flow and are neutralized, is under 150 - 300 $w/cm^2$. The heat load on the side edges of the valves $w_v$ is most serious. This is given as $w_v \sim w\theta$ where the intersect angle of the valves with magnetic force lines $\theta = \theta_1 - \theta_2$, $\theta_1 \sim (B_\theta/B_z)$, and $\theta_2 \leq \frac{2}{3}\theta_1$ since setting accuracy of the valves is the order of $\theta_1$. Therefore $w_v$ is several 100 $w/cm^2$ and it will give rapid damage of the valve edges.

However, these valves are easily repaired owing to their structural simplicity, and this is one of the major advantages of these valves comparing with the divertor plates of the poloidal divertor.

## 3.2 Pumping Requirements

Here we discuss about pumping requirements. Most of helium particles flow in the boundary layer along the toroidal field lines with the width H, which is given by $N_{He}/\tau_{He} = 2\pi\sqrt{ab}H(n_{He})_b v_s = A(n_{He})v_s(B_r/B_z)$. Therefore the necessary valve height h is given by $h = (H/10)(2\pi\sqrt{ab}/ab_v N) = (2\pi R/10)(B_r/B_z)(\pi\sqrt{ab}/b_v N) \sim 10^{-2}$ m. Where we assume $B_r/B_z \sim 1/500$, valve width $b_v = 0.1$ (m) and valve number $N = 20$. The total opening area of the valves $A_v = 2\ell_v hN = 0.5$ m$^2$ where the valve length $\ell_v = 1.2$ m.

Plasma particles and helium are not ionized in the plasma flowing into the backsides of the valves. Therefore we can simply calculate the neutral flows such as direct leakage flows $\Gamma_\ell$ through the valve opening and pumped flows $\Gamma_v$ through the ports.

$$\Gamma_\ell = \frac{1}{4} n_0 v_0 A_v \ ,$$

$$\Gamma_v = n_0 S_p \sim \frac{1}{10} \frac{N_p}{\tau_p} = 2.5 \times 10^{21} \ (\mathrm{p/s})$$

where we assume $n_0 = n_D^0 + n_T^0 + n_{He}^0$ , $n_{He}^0/(n_D^0 + n_T^0) \sim 0.1$, the particle confinement time $\tau_p = 1S$, $V_0 \sim 10^3/S$ and $S_p$ is the pumping speed at the port inlet (the pumping speed at the outlet should be larger than $S_p$ by several factor). Therefore $\Gamma_v \gtrsim \Gamma_\ell$ when $S_p \geq 10^2$ m$^3$/S. We employ $S_p = 5 \times 10^2$ m$^3$/S and neutral density in the port $n_0 \sim 5 \times 10^{18}$ p/m$^3$. Neutral backflow does not prevent the inflow of the plasma particles, since $\Gamma_\ell \ll n_b v_s A_v$ where the boundary density $n_b = \frac{2\overline{n}}{\tau_p}\left(\frac{1}{v_s}\right)\left(\frac{B_z}{B_r}\right) = 3 \sim 5 \times 10^{18}$ (p/m$^3$) assuming the boundary temperature $T_b = 10^2 \sim 10^3$ eV.

## 4. PLASMA-WALL INTERACTIONS IN "WALL LAPPING PLASMA"

In above considerations, we assumed that the particle confinement time of helium is an order of one second, and did not discuss in detail about a problem of the plasma contamination by the first wall material due to sputtering by impurity ions. These strongly depends on the transport phenomenas of the plasma and the impurities as follows.

However, these valves are easily repaired owing to their structural simplicity, and this is one of the major advantages of these valves comparing with the divertor plates of the poloidal divertor.

## 3.2 Pumping Requirements

Here we discuss about pumping requirements. Most of helium particles flow in the boundary layer along the toroidal field lines with the width H, which is given by $N_{He}/\tau_{He} = 2\pi\sqrt{ab}H(n_{He})_b v_s = A(n_{He})v_s(B_r/B_z)$. Therefore the necessary valve height h is given by $h = (H/10)(2\pi\sqrt{ab}/ab_v N) = (2\pi R/10)(B_r/B_z)(\pi\sqrt{ab}/b_v N) \sim 10^{-2}$ m. Where we assume $B_r/B_z \sim 1/500$, valve width $b_v = 0.1$ (m) and valve number $N = 20$. The total opening area of the valves $A_v = 2\ell_v hN = 0.5$ m$^2$ where the valve length $\ell_v = 1.2$ m.

Plasma particles and helium are not ionized in the plasma flowing into the backsides of the valves. Therefore we can simply calculate the neutral flows such as direct leakage flows $\Gamma_\ell$ through the valve opening and pumped flows $\Gamma_v$ through the ports.

$$\Gamma_\ell = \frac{1}{4} n_0 v_0 A_v \ ,$$

$$\Gamma_v = n_0 S_p \sim \frac{1}{10} \frac{N_p}{\tau_p} = 2.5 \times 10^{21} \ \text{(p/s)}$$

where we assume $n_0 = n_D^0 + n_T^0 + n_{He}^0$ , $n_{He}^0/(n_D^0 + n_T^0) \sim 0.1$, the particle confinement time $\tau_p = 1S$, $V_0 \sim 10^3/S$ and $S_p$ is the pumping speed at the port inlet (the pumping speed at the outlet should be larger than $S_p$ by several factor). Therefore $\Gamma_v \gtrsim \Gamma_\ell$ when $S_p \geq 10^2$ m$^3$/S. We employ $S_p = 5 \times 10^2$ m$^3$/S and neutral density in the port $n_0 \sim 5 \times 10^{18}$ p/m$^3$. Neutral backflow does not prevent the inflow of the plasma particles, since $\Gamma_\ell \ll n_b v_s A_v$ where the boundary density $n_b = \frac{2\overline{n}}{\tau_p}\left(\frac{1}{v_s}\right)\left(\frac{B_z}{B_r}\right) = 3 \sim 5 \times 10^{18}$ (p/m$^3$) assuming the boundary temperature $T_b = 10^2 \sim 10^3$ eV.

## 4. PLASMA-WALL INTERACTIONS IN "WALL LAPPING PLASMA"

In above considerations, we assumed that the particle confinement time of helium is an order of one second, and did not discuss in detail about a problem of the plasma contamination by the first wall material due to sputtering by impurity ions. These strongly depends on the transport phenomenas of the plasma and the impurities as follows.

(1) The particle confinement time of ash in the hot core region should be shorter than 10 seconds and the average confinement time should be shorter than above one by an order of magnitude, i.e. most of ash recycle at the periphery and consequently the particle flux of ash to the wall should be larger than that from the hot core region, when we assume the allowable ash accumulation is 10% of the plasma density considering small margin of the beta value.

(2) In a large tokamak without the divertor, the edge temperature should be lower than 50 - 100 eV [14] except the case where low Z materials are employed for the first wall and their chemical sputtering yields are not large (e.g. below a few $10^{-2}$ atoms/ion). It is because in a case of metallic materials for the first wall the high edge temperature will cause large amount of the impurity production due to sputtering by plasma particles, and the impurity multiplication by self sputtering.

In recent experimental results show that the density profiles are sharp in small-size tokamaks and even in a mid-size tokamak such as PLT. In order to explain such results, a strong inward flow such by Ware pinch [15] effect is necessary to be considered. When we extrapolate the above model in a large-size tokamak, the particle confinement of helium in the hot core region is likely to be longer than ten seconds and consequently ash accumulation will be large. However, it is not obvious whether high ash accumulation is fetal problem or not, since the beta limitation and what will cause excess beta have not been made clear. They are left open to future experiments.

On the otherhand in the above model, most of plasma particles still recycle at the periphery and consequently the edge temperature is reduced. If the flow rate of the recycling one and diffusing one from the hot core region is larger than twenty, the edge temperature should be lower than 100 eV. Above result is estimated by following edge temperature scaling given by DIVA experiments [16]

$$T_{eb} = \frac{3}{2\gamma}\left(\frac{P_c}{P_\alpha}\right)(\bar{T}_e + \bar{T}_i)\left(\frac{\tau_p}{\tau_E}\right) \qquad \text{(eV)}$$

where $\gamma$ is the heat transport rate (usually $\gamma = 8 \sim 15$), $\tau_E$ is the energy confinement time, and $P_c$ is conduction and convection loss leakaging

from the plasma. When we assume $P_c \sim 0.8\ P_\alpha$, $\overline{T}_e \sim \overline{T}_i \sim 10$ keV, and $\tau_E \sim 20\ \tau_p$, $T_{eb} = 80 \sim 150$ eV. In this case we can employ metallic first wall.

If $\tau_p$ is longer than $\tau_E/20$, low Z first wall should be employed because of high edge temperature. However, metallic materials can be used for the valves, since sputtered atoms from the valves is negligible (i.e. only 1 - 2% of the plasma particles will hit the front surface of the valves), and then the valves with cooling mechanisms can bear high heat load.

## ACKNOWLEDGMENTS

We would like to thank Drs. M. Yoshikawa and Y. Shimomura for their helpful comments and discussions. Substantial contributions to this paper have been made by Dr. M. Kasai, Messrs. T. Hirayama and T. Kuroki in estimating magnetic islands and plasma-wall interactions.

We would also express our gratitude to Drs. S. Mori and Y. Iso for their continuing encouragement.

## REFERENCES

[1] Y. Shimomura, K. Sako, K. Shinya; JAERI-M 8294 (1979).

[2] T. Tazima; J. Nuclear Materials, 76 & 77 (1978) 594.

[3] F. Karger, K. Lackner; Phys. Letters 13 (1977) 385.

[4] W. Feneberg; Proc. 8th Europ. Conf. on Controlled Fusion and Plasma Physics, Prague, 1 (1977) 4 .

[5] M. Azumi; private communication.

[6] S. Matsuda, M. Yoshikawa, JAERI-M 4842 (1972).

[7] A. I. Morozov, L. S. Solov'ev; Rev. of Plasma Physics, vol. 2, p. 1 (ed. by M. A. Leontovich) Consultants Bureau, New York 1966.

[8] M. N. Rosenbluth, R. Z. Sagdeev, J. B. Taylor, G. M. Zaslavsky; Nuclear Fusion 6 (1966) 297.

[9] N. N. Filorenko, R. Z. Sagdeev, G. M. Zaslavsky; Nuclear Fusion 7 (1967) 253.

[10] Y. Tomita, S. Seki, H. Momota; J. Phys. Soc. Japan 42 (1977) 687.

[11] Y. Tomita, Y. Nomura, H. Momota, R. Itatani; J. Phys. Soc. Japan 44 (1978) 637.

[12] J. A. Krommes, P. G. Kleva, C. Oberman; PPPL-1389 (1978).

from the plasma. When we assume $P_c \sim 0.8\ P_\alpha$, $\overline{T}_e \sim \overline{T}_i \sim 10$ keV, and $\tau_E \sim 20\ \tau_p$, $T_{eb} = 80 \sim 150$ eV. In this case we can employ metallic first wall.

If $\tau_p$ is longer than $\tau_E/20$, low Z first wall should be employed because of high edge temperature. However, metallic materials can be used for the valves, since sputtered atoms from the valves is negligible (i.e. only 1 - 2% of the plasma particles will hit the front surface of the valves), and then the valves with cooling mechanisms can bear high heat load.

## ACKNOWLEDGMENTS

We would like to thank Drs. M. Yoshikawa and Y. Shimomura for their helpful comments and discussions. Substantial contributions to this paper have been made by Dr. M. Kasai, Messrs. T. Hirayama and T. Kuroki in estimating magnetic islands and plasma-wall interactions.

We would also express our gratitude to Drs. S. Mori and Y. Iso for their continuing encouragement.

## REFERENCES

[1] Y. Shimomura, K. Sako, K. Shinya; JAERI-M 8294 (1979).

[2] T. Tazima; J. Nuclear Materials, 76 & 77 (1978) 594.

[3] F. Karger, K. Lackner; Phys. Letters 13 (1977) 385.

[4] W. Feneberg; Proc. 8th Europ. Conf. on Controlled Fusion and Plasma Physics, Prague, 1 (1977) 4 .

[5] M. Azumi; private communication.

[6] S. Matsuda, M. Yoshikawa, JAERI-M 4842 (1972).

[7] A. I. Morozov, L. S. Solov'ev; Rev. of Plasma Physics, vol. 2, p. 1 (ed. by M. A. Leontovich) Consultants Bureau, New York 1966.

[8] M. N. Rosenbluth, R. Z. Sagdeev, J. B. Taylor, G. M. Zaslavsky; Nuclear Fusion 6 (1966) 297.

[9] N. N. Filorenko, R. Z. Sagdeev, G. M. Zaslavsky; Nuclear Fusion 7 (1967) 253.

[10] Y. Tomita, S. Seki, H. Momota; J. Phys. Soc. Japan 42 (1977) 687.

[11] Y. Tomita, Y. Nomura, H. Momota, R. Itatani; J. Phys. Soc. Japan 44 (1978) 637.

[12] J. A. Krommes, P. G. Kleva, C. Oberman; PPPL-1389 (1978).

from the plasma. When we assume $P_c \sim 0.8\ P_\alpha$, $\overline{T}_e \sim \overline{T}_i \sim 10$ keV, and $\tau_E \sim 20\ \tau_p$, $T_{eb} = 80 \sim 150$ eV. In this case we can employ metallic first wall.

If $\tau_p$ is longer than $\tau_E/20$, low Z first wall should be employed because of high edge temperature. However, metallic materials can be used for the valves, since sputtered atoms from the valves is negligible (i.e. only 1 - 2% of the plasma particles will hit the front surface of the valves), and then the valves with cooling mechanisms can bear high heat load.

## ACKNOWLEDGMENTS

We would like to thank Drs. M. Yoshikawa and Y. Shimomura for their helpful comments and discussions. Substantial contributions to this paper have been made by Dr. M. Kasai, Messrs. T. Hirayama and T. Kuroki in estimating magnetic islands and plasma-wall interactions.

We would also express our gratitude to Drs. S. Mori and Y. Iso for their continuing encouragement.

## REFERENCES

[1] Y. Shimomura, K. Sako, K. Shinya; JAERI-M 8294 (1979).

[2] T. Tazima; J. Nuclear Materials, 76 & 77 (1978) 594.

[3] F. Karger, K. Lackner; Phys. Letters 13 (1977) 385.

[4] W. Feneberg; Proc. 8th Europ. Conf. on Controlled Fusion and Plasma Physics, Prague, 1 (1977) 4 .

[5] M. Azumi; private communication.

[6] S. Matsuda, M. Yoshikawa, JAERI-M 4842 (1972).

[7] A. I. Morozov, L. S. Solov'ev; Rev. of Plasma Physics, vol. 2, p. 1 (ed. by M. A. Leontovich) Consultants Bureau, New York 1966.

[8] M. N. Rosenbluth, R. Z. Sagdeev, J. B. Taylor, G. M. Zaslavsky; Nuclear Fusion 6 (1966) 297.

[9] N. N. Filorenko, R. Z. Sagdeev, G. M. Zaslavsky; Nuclear Fusion 7 (1967) 253.

[10] Y. Tomita, S. Seki, H. Momota; J. Phys. Soc. Japan 42 (1977) 687.

[11] Y. Tomita, Y. Nomura, H. Momota, R. Itatani; J. Phys. Soc. Japan 44 (1978) 637.

[12] J. A. Krommes, P. G. Kleva, C. Oberman; PPPL-1389 (1978).

[13] J. F. Shivell; PPPL-1342 (1977).
[14] S. Sengoku, et al.; Submitted to Nuclear Fusion.
[15] A. A. Ware; Phys. Rev. Lett. 25 (1970) 916.
[16] DIVA Group; Nuclear Fusion, 18 (1978) 12.

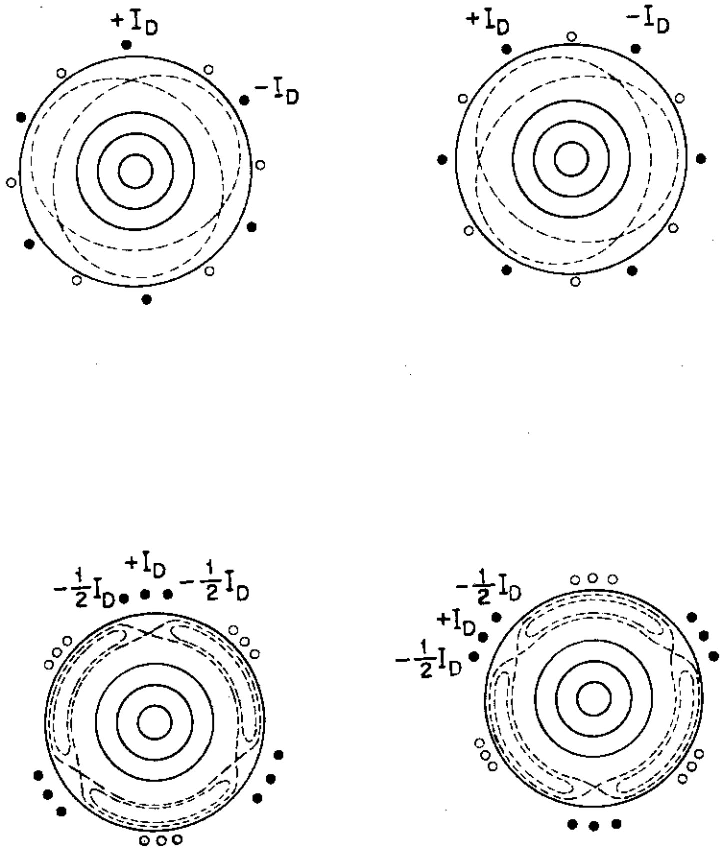

Fig. 1 Schematic pictures of the cross section of a helical island with resonance at $q = 3$. Two sets of helical coil currents are quickly changed alternately.

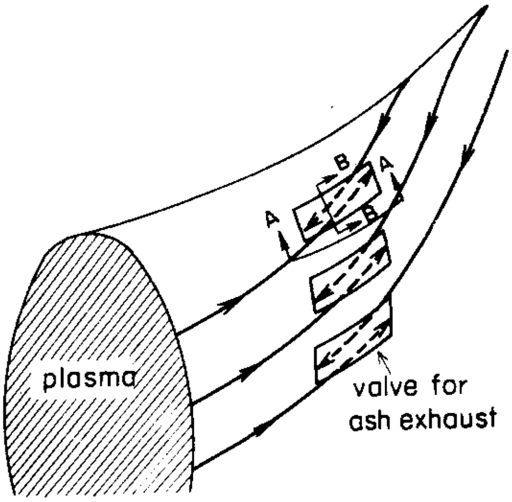

Fig. 2(a) Location of mechanical valve for ash exhaust in toroidal geometry.

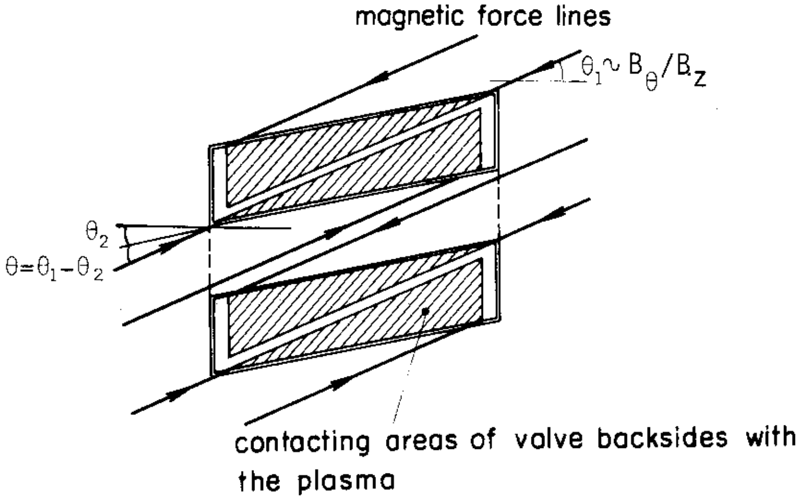

Fig. 2(b) Relation between the valves and magnetic field lines

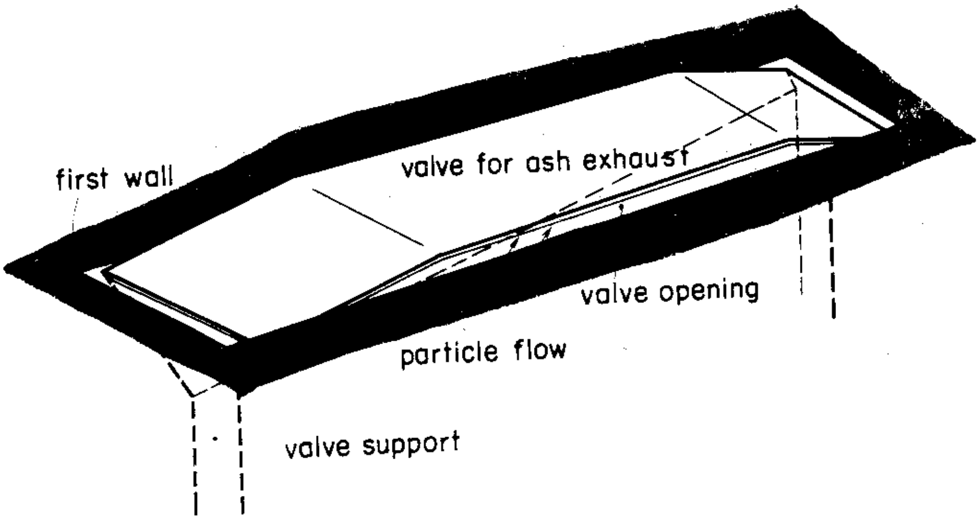

Fig. 2(c) The oblique view of the valve.

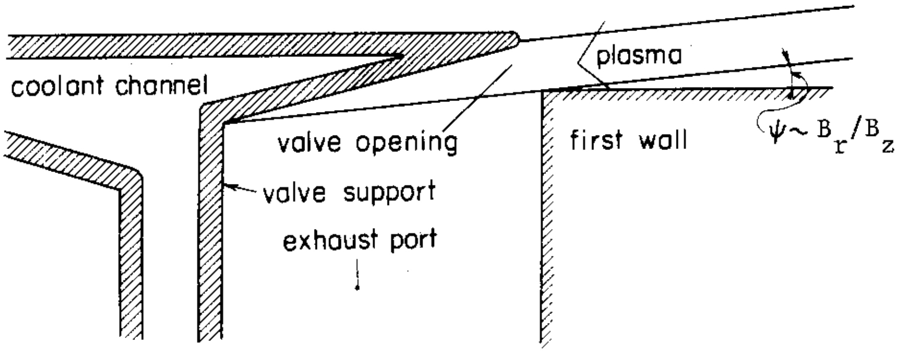

Fig. 2(d) A-A view of the valve of Fig. 2(a).

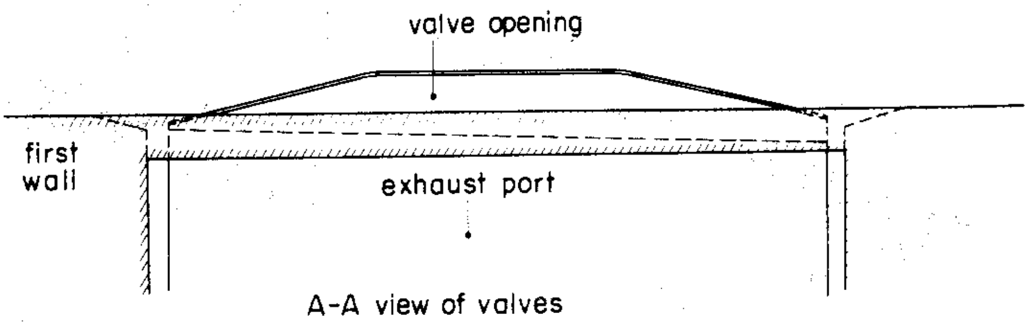

Fig. 2(e) B-B view of the valve of Fig. 2(a).

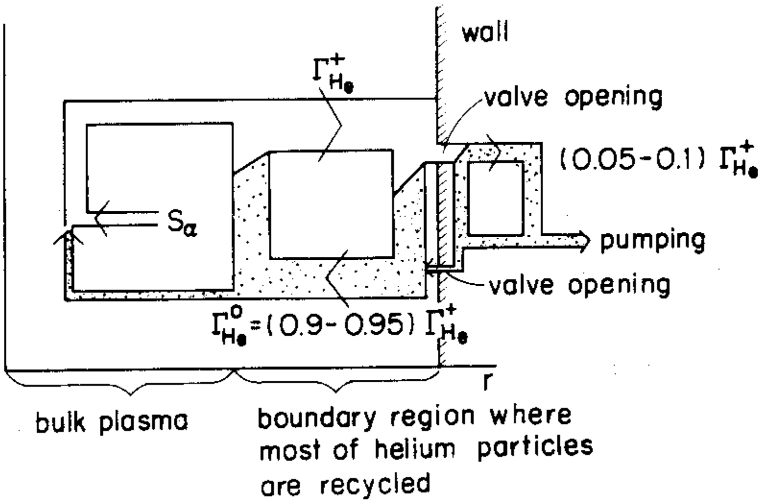

Fig. 3 Schematic picture of ash particle recycling and exhaust.

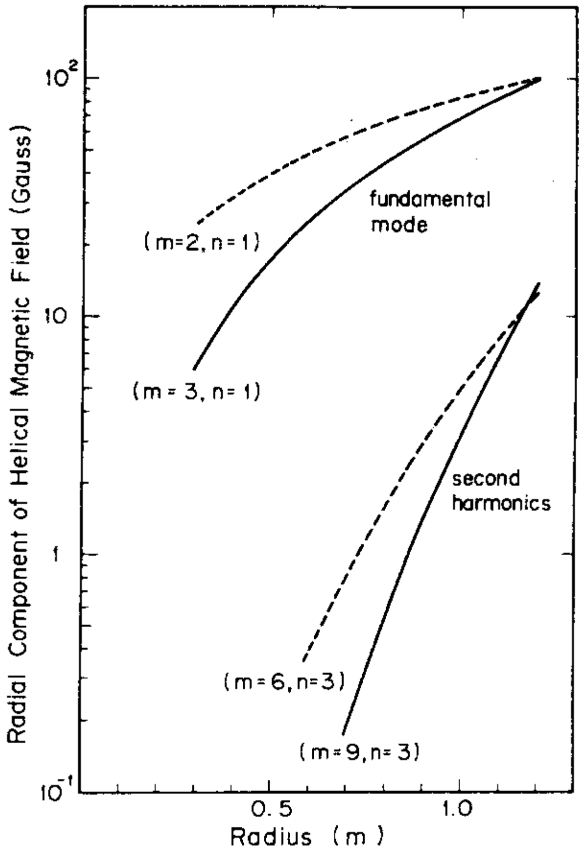

Fig. 4 Radial component of helical magnetic field by external helical windings. Fundamental and second harmonics are shown. Solid lines are the case of $q = 3$ resonance ($\ell = 3$) and dotted lines are the case of $q = 2$ resonance ($\ell = 2$).

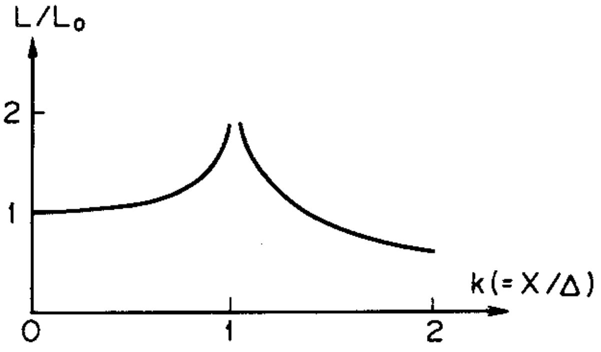

Fig. 5 Length of the field line when it circulates the island.