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Radial Electric Field and Transport near the Rational Surface and the Magnetic Island in LHD

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Abstract.
The structure of the radial electric field and heat transport at the magnetic island in the Large Helical Device is investigated by measuring the radial profile of poloidal flow with charge exchange spectroscopy. The convective poloidal flow inside the island is observed when the n/m=1/1 external perturbation field becomes large enough to increase the magnetic island width above a critical value (15-20% of minor radius) in LHD. This convective poloidal flow results in a non-flat space potential inside the magnetic island. The sign of the curvature of the space potential depends on the radial electric field at the boundary of the magnetic island. The heat transport inside the magnetic island is studied with a cold pulse propagation technique. The experimental results show the existence of the radial electric field shear at the boundary of the magnetic island and a reduction of heat transport inside the magnetic island

1. Introduction

The structure of the magnetic island is observed in various plasma parameters. The electron temperature profiles measured with Thomson scattering or ECE signals shows flattening inside the magnetic island. [1,2]. On the other hand, density profile peaking inside the magnetic island is observed in TEXTOR and JET[3-5]. The density peaking is more significant when particles are fueled into the magnetic island by a pellet , which is observed in soft-X ray signals as a " snake" modulation in JET. If the space potential is not flat inside the magnetic island, both the radial electric field and the poloidal flow should be finite inside the magnetic island. Because of the conservation of particle flux inside the magnetic island, the poloidal flow should be convective, if it exists inside the magnetic island. When the poloidal flow is convective, the sign of the radial electric field should be reversed across the center of the magnetic island and radial electric field shear should appear inside the magnetic island. Although the structure of radial electric field and radial electric field shear are crucial parameters to understand the good confinement (low diffusivity) inside the magnetic island, there have been no clear measurements of poloidal flow or radial electric field inside the magnetic island except at the plasma edge[6].

The Large Helical Device (LHD) [7] is a Heliotron device (poloidal period number L = 2, and toroidal period number M = 10) with a major radius of R_{ax} =3.5 – 4.1 m, an average minor radius of 0.6 m, magnetic field up to 3 T. The radial electric field (E_r) is derived from the poloidal and toroidal rotation velocity and pressure gradient of Neon impurity measured with charge exchange spectroscopy[8] at the mid plane in LHD (vertically elongated cross section) using a radial force balance. The radial force balance equation can be expressed as $E_r = (en_IZ_I)^{-1}(\partial p_I/\partial r) - (v_\theta B_\phi - v_\phi B_\theta)$, where B_ϕ and B_θ are toroidal and poloidal magnetic field and Z_I, n_I, p_I are the ion charge, density and pressure of the measured impurity, respectively.

2. Magnetic island produced by the n/m=1/1 perturbation coil

The Large Helical Device (LHD) has n/m=1/1 external perturbation coils. The size of magnetic island can be controlled up to 10cm by changing the current of the perturbation coils. The spatial resolution of the measurements of the radial electric field using the charge exchange spectroscopy is determined by the length of integration of the signal along the line of sight within the beam width of the neutral beam. The spatial resolution becomes poor near the plasma center and relatively good near the plasma edge and it is +/– 1.5cm at the R=4.05m.

Figure 1(a) shows the poloidal cross section of the last closed magnetic flux surface and magnetic island calculated (with zero beta) for the discharge with the n/m=1/1 external perturbation coil current of -1200A and electron temperature and density profiles. The magnetic island is located near the plasma edge at $\rho = 0.85$. As shown in Fig.1(b) and (c), the flattening of electron density and temperature and ion temperature are observed for the plasmas with an island and convective poloidal flow ($I_{n/m=1/1}$ = 1200A, $\langle n_e \rangle = 2.1\times10^{19}$m^{-3}) and without ($I_{n/m=1/1}$ = 390A, $\langle n_e \rangle = 2.2\times10^{19}$m^{-3}) an island as a reference. The magnetic field B is 2.83T with a vacuum magnetic axis of 3.5m. The flattening width of the electron temperature is considered to represent the width of the magnetic island in the plasma, which would not be identical to the width of the vacuum magnetic island due to the healing effect[2]. Since there is no pressure gradient inside the magnetic island, one can expect a flat space potential and zero radial electric field inside the magnetic island.

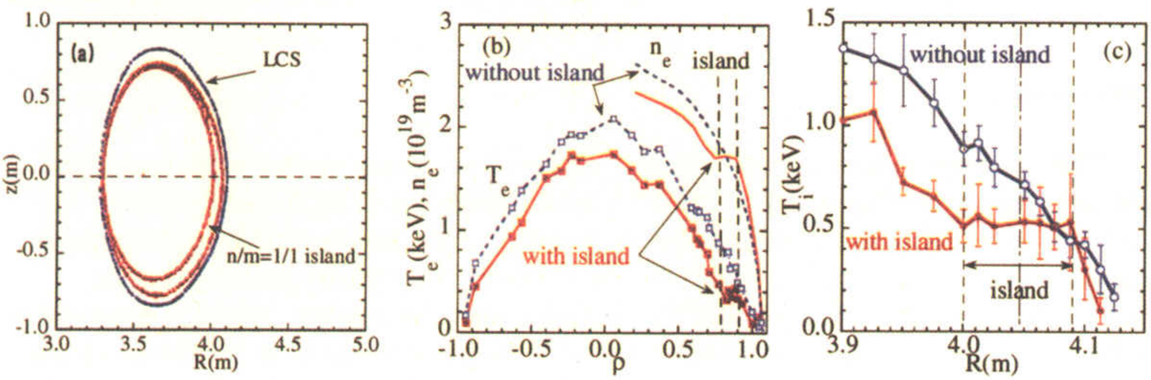

Fig.1 (a) Magnetic flux surface with 1/1 magnetic island and radial profiles of (a) electron density and temperature and (c) ion temperature profiles with and without 1/1 magnetic island.

The current of n/m=1/1 external perturbation coils is varied in a wide range from 260A to 1200A for the plasma with the magnetic field of 1.5T and vacuum magnetic axis of 3.5m and the averaged density of $<n_e> = 1.2\times10^{19}m^{-3}$. When the current of n/m=1/1 external perturbation coils is small (see 260A case in Fig.2), no island structure appears in the profile of the radial electric field. As the perturbation coil current increases, the clear structure of the magnetic island appears in the radial electric field[9]. As the perturbation coil current increases, the width of the magnetic island estimated from the radial profiles of radial electric field also increases up to 9 cm, which corresponds to 17 % of the averaged minor radius. The large shear of the radial electric field is observed at the boundary of the magnetic island (R=4.00m and R=4.09m).

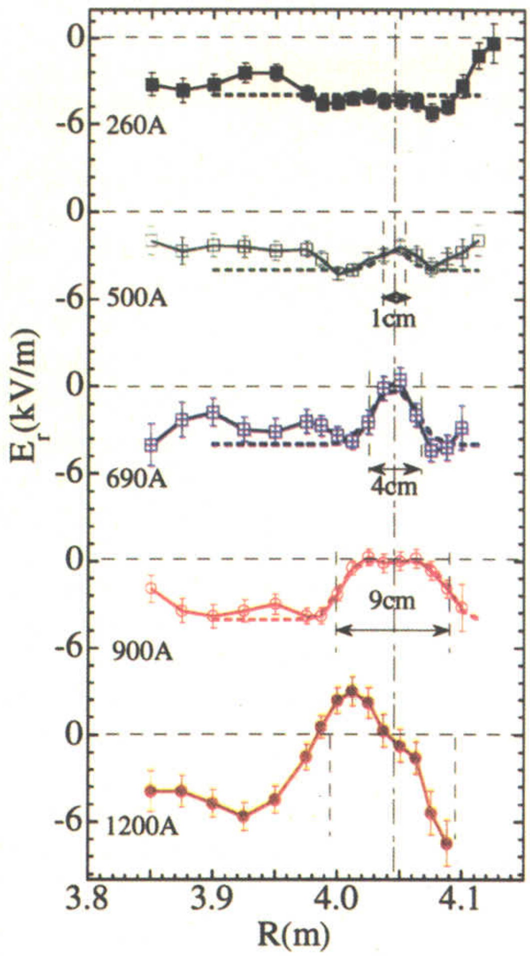

Fig.2 Radial profiles of radial electric field for various current of n/m=1/1 perturbation coil

The bifurcation phenomena of plasma flow inside the magnetic island is observed. When the current of n/m=1/1 external perturbation coils, $I_{n/m=1/1}$, becomes large enough (see 1200A in Fig.2), the finite radial electric field appears inside the magnetic island. The radial electric field is zero at the center of the magnetic island and the sign of the radial electric field is reversed across the center of the island. The plasma flow inside the magnetic island is due to the imbalance of the viscous force between the two boundaries at the O-point of the magnetic island and the direction of the flow is determined by the sign of the radial electric field shear at the X-point of the magnetic island. The plasma flow velocity inside the magnetic island should be proportional to the square of the island width, W, as $v = (W^2/4\delta)(dV_\theta/dr)$, where δ is the shear width at the boundary of the magnetic island, if the viscous force at the boundary of the magnetic island is linearly proportional to the flow shear. Non-linearity of the viscous force [10] is required to cause the sudden appearance of plasma flow inside the magnetic island.

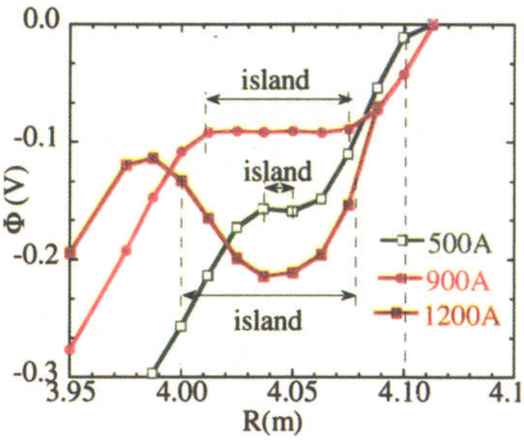

Fig.3 Radial profiles of space potential for various current of n/m=1/1 perturbation coil

The flattening of space potential as well as ion temperature and electron temperature is observed inside the magnetic island, when the perturbation field is small as seen in Fig.3. However the convective poloidal flow inside the island is observed when the magnetic island width exceeds a critical value (15-20 %) of the minor radius. This convective poloidal flow results in a non-flat space potential ($d^2\Phi/dr^2 > 0$) inside the magnetic island, while keeping the same values of space potential at the both sides of the boundary of the magnetic island. The sign of the curvature of the space potential is determined such as to decrease the shear of poloidal flow at the boundary of the magnetic island.

3. Cold pulse propagation inside the magnetic island.

Since the radial profiles of electron temperature show a flattening inside the magnetic island, the transport analysis based on the temperature gradient and radial heat flux in the steady state is invalid. The localized flattening of the electron temperature profile is due to a modification of the magnetic topology resulting from the magnetic island produced by the perturbation field and not due to the increase of energy transport. Significant reduction of energy transport is expected inside the magnetic island, because there is no pressure driven turbulence. When there is no local heating inside the magnetic island, the electron temperature profile shows flattening even though the magnitude of the thermal diffusivity is small inside the magnetic island. In order to evaluate the transport inside the magnetic island, the response of the electron temperature to the cold pulse produced by a tracer-encapsulated solid pellet (TESPEL)[11] is investigated inside or at the boundary of the magnetic island[12].

As seen in Fig.4, the electron temperature profile measured with a ECE radiometer for the plasma with a magnetic axis of 3.5m and the magnetic field of 2.88T and with the n/m=1/1 external perturbation coil current of -1800A and the averaged density of $\langle n_e \rangle = 1.7\times10^{19} m^{-3}$. There is a clear flattening of the electron temperature observed at the O-point of the magnetic island, while there is no flattening observed at the X-point of the magnetic island. The ECE radiometer is located at the inboard side and TESPEL is injected from the outboard side of LHD 72 degrees apart in toroidal direction. Therefore when the measurement of the ECE radiometer is located at the X-point of the magnetic island, TESPEL is injected into the O-point and the cold pulse starts from the magnetic island. The cold pulse propagates inward (R > 2.905m) and outward (R < 2.905m) from the X-point of the magnetic island. On the other hand, when the measurement of the ECE radiometer is located at the O-point of the magnetic island, TESPEL is injected into the X-point and the cold pulse starts from the boundary of the magnetic island (R = 2.95m). Then the cold pulse propagates both inside (R < 2.95m) and outside (R > 2.95m) the magnetic island. The drop of the electron temperature due to the cold pulse is less than 10% of the electron temperature.

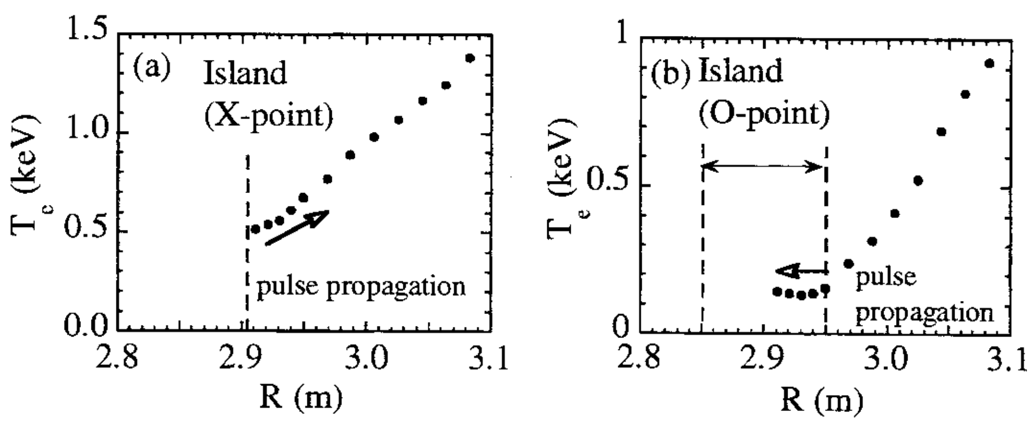

Fig.4 Radial profiles of electron temperature at the (a) X-point and (b) O-point of the magnetic island measured with ECE just before the TESPEL is injected.

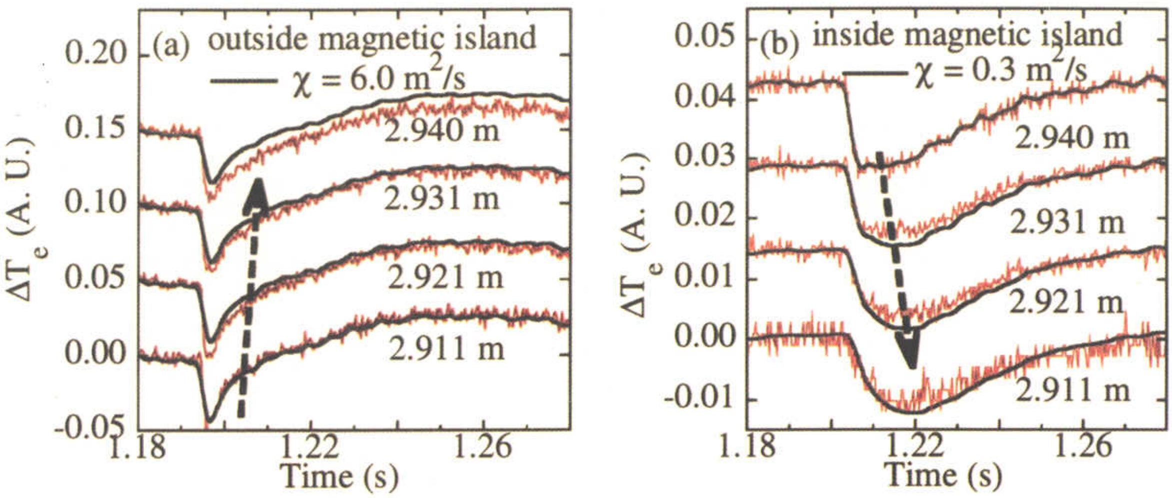

Fig.5 The time evolution of electron temperature measured with ECE (a) outside and (b) inside the magnetic island for the plasma where the TESPEL is injected.

As shown in Fig.5, the response time of the cold pulse inside the magnetic island is much longer than that observed outside of the magnetic island. The amplitude of the cold pulse is also smaller inside the magnetic island than outside of the island. The time delay and amplitude of the electron temperature of the cold pulse inside the magnetic island is reproduced by simulation of the cold pulse propagation in a slab mode with a low thermal diffusivity of $0.3m^2/s$, which is smaller than that ($6m^2/s$) outside the magnetic island by more than one order of magnitude. Because the structure of the magnetic island (the effect of poloidal asymmetry) is not included in the analysis, the estimate of the absolute value of the thermal diffusivity is rather crude. However, the differences in pulse propagation inside and outside the magnetic island clearly demonstrate the reduction of energy transport inside the magnetic island.

In conclusion, the structure of the radial electric field and heat transport at the magnetic island in LHD is investigated. The experimental results show 1) the existence of radial electric field shear at the boundary of the magnetic island, 2) plasma flow inside the magnetic island when the width of the magnetic island is large enough and 3) reduction of heat transport inside the magnetic island.

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