§39. Diamagnetic Flux Measurements in LHD

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The stored energy has been estimated by diamagnetic flux measurements in LHD. The superconducting coils have produced the steady -state magnetic field with a negligible amount of ripple, and it is favorable for the measurement of change in toroidal flux due to equiriblium currents. However, there are two kinds of problems to be solved to estimate the toroidal flux accurately. One is poloidal coupling between diamagnetic currents and some structures such as vacuum vessel, helical coils, shell arms and magnetic supporting structure, and the other is toroidal coupling between plasma currents and helical structures. If net plasma currents exist, they induce eddy currents on helical structures and the helical currents produce the toroidal flux. In particular, eddy currents on helical coils, which are not attenuated because of long L/R time, prevent the flux measurements even in steady-state discharges. In LHD, the diamagnetic flux has been measured with diamagnetic loops inside vacuum vessel and compensated by direct measurements of eddy currents flowing some complex structures.

The diamagnetic loop signal is described as

$$\Phi_{loop}=\Phi_{plasma}+\Phi_{VV}+\Phi_{HC}+\Phi_{SA}+\Phi_{SP} \qquad (1)$$

where Φ_{loop} is toroidal flux measured with the diamagnetic loop, and Φ_{vv}, Φ_{hc}, Φ_{sa} and Φ_{sp} are due to poloidal eddy currents on vacuum vessel, helical coils, shell arms and magnetic supporting structure, respectively. The helical currents on helical structures (helical coil and shell arms) and poloidal shell currents are directly measured with Rogowski coils inside Cryostat, and vacuum vessel currents is not measured. Each mutual inductance between diamagnetic loop and some structures is directly measured or calculated using Biot-Savart method. Figure 1 shows the changes of toroidal fluxes observed in NBI discharge with pellet injection. In this discharge, the W_p reaches about 200kJ at 0.9 s and the net plasma currents reach about 10 kA in the co-direction, and the helical coil currents flow in the diamagnetic direction to shield the flux produced by the plasma currents. Figure 2 shows toroidal fluxes included in the diamagnetic loop signals as a function of net plasma currents when the stored energy has maximum value in each discharge. The discharges with hydrogen gas have been performed within 2 second so far, and the net toroidal currents have been observed in the range from -13kA to 10kA, where the positive current is defined as the counter direction. Both the toroidal fluxes due to helical coil and shell currents are dominant components of the diamagnetic signals, and helical coil component strongly depends on the net plasma currents.

The Φ_{plasma} can be expressed as the summation of diamagnetic flux Φ_{dia}, paramagnetic flux Φ_{para} as well as that in tokamaks and dia(para)magnetic flux $\Phi_{helical}$ which is produced by the helical currents flowing along rotational transform produced by external magnetic coils. Both Φ_{para} and $\Phi_{helical}$ linearly depend on the plasma currents as shown in Fig.2. In the low W_p case, the ratio of the summation of the Φ_{para} and the $\Phi_{helical}$ to the Φ_{dia}, reaches about 20 % because the beam driven currents is relatively large as indicated in Fig. 3. This ratio decreases with the W_p and reaches about a few %, and it is almost negligible as shown in Fig 1.

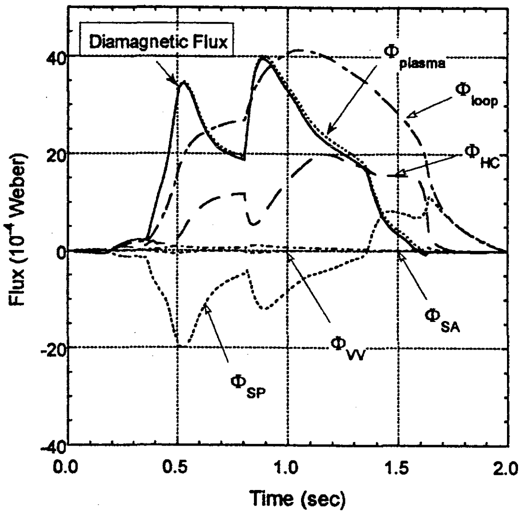

Fig.1 Changes of toroidal fluxes produced by eddy currents in NBI discharge with the pellet injection.

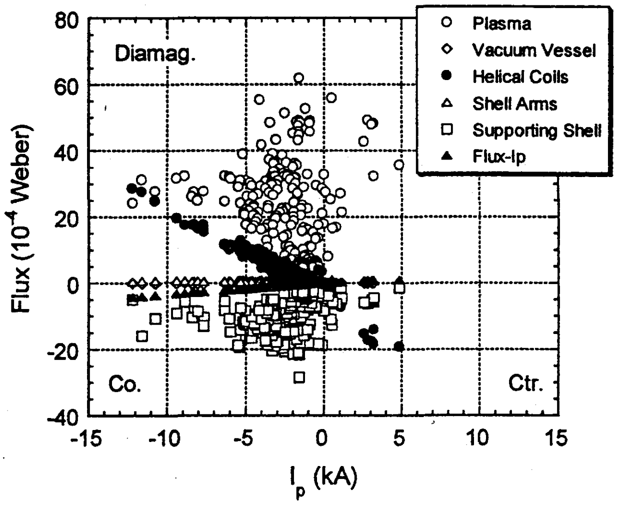

Fig 2 Flux components included in the diamagnetic loop signals as a function of net plasma currents.

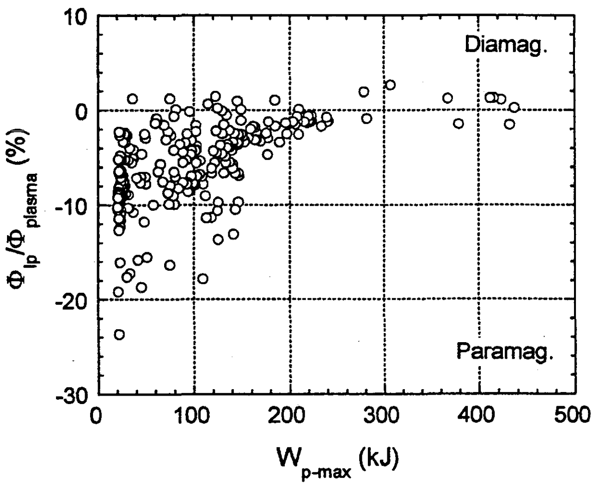

Fig.3 Change of the ratio of Φ_{ip} to Φ_{plasma} as a function of W_p.