High-Resolution 2D Magnetic Field Measurement of Magnetic Reconnection Using Printed-Circuit Board Coils

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2D high-resolution magnetic probe arrays for local 2D magnetic field measurements of magnetic reconnection have been developed using advanced printed-circuit board (PCB) technology. Each of these arrays can be equipped with all three components of magnetic pickup coils ($5 \times 3\,\mathrm{mm}^2$). Each coil is composed of a two-sided coil circuit pattern with a line width of 0.05 mm. Based on this new probe technique, we conducted high-resolution and high-accuracy measurements of the current sheet to determine the formation and ejection of plasmoid in a current sheet of two merging tokamak plasmas for the first time.

Keywords: plasma diagnostics, magnetic probe, printed-circuit board, magnetic reconnection, plasmoid

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Magnetic probe arrays have been widely used for internal and external magnetic field measurements in various plasma experiments for fusion applications, plasma physics, and space physics [1–3]. Detailed 2D measurements of the magnetic field are essential when studying magnetic reconnection [4]. Their X-point structures are composed of sheet currents whose thicknesses are as thin as ion gyroradii [5], indicating that their measurement requires the same order of high spatial resolution. Thus, it is crucial to determine the ways in which both the density and accuracy of the pickup coil array can be improved for high-resolution measurements of the magnetic field of reconnection.

We developed 2D high-resolution magnetic probe arrays using printed-circuit board (PCB) technique. The advantages of PCB technology are as follows:

(1) high accuracy of coil cross section,
(2) highly accurate coil orientation and spacing,
(3) easily manufactured high-density coil array,
(4) installation of two or three component coils and increase in the number of turns by multi-layer printed-circuits.

These features cannot be realized by conventional pickup coils, e.g., chip inductors. Replacing the conventional coil array with the PCB coil array increases the special resolution of the coil array from 5 to 15 coils in 15 cm.

The PCB-type coil arrays were tested in a TS-3U merging device. The cylindrical vacuum vessel of this device has a diameter of 0.75 m and a length of 1.17 m and is equipped with two internal poloidal field coils, each with a radius of 0.22 m for the two Spherical Tokamak (ST) formation. The two STs ($R \sim 0.2$ m, $R/a \sim 1.5$) are merged

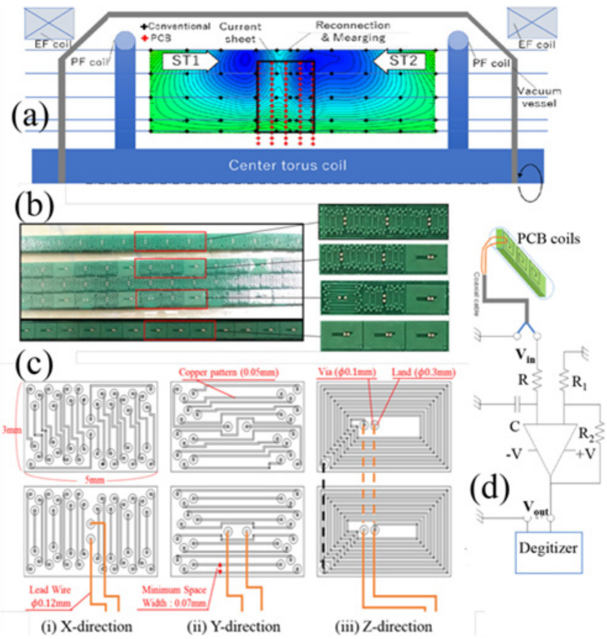

Fig. 1 (a) 2D setup of conventional pickup coils (black crosses) and PCB coils (red crosses) on the *r*-*z* poloidal flux contour of two merging ST plasmas. (b) Four types of PCB probe arrays composed of (c) three coil circuit patterns on for B_x, B_y, and B_z. (d) Integrating and amplifying circuits for each PCB coil for the magnetic field measurement.

together in the axial direction.

Figure 1 (a) shows the experimental setups of the conventional and PCB pickup coil arrays in a TS-3U device. Each probe is covered by a thin glass tube with an outer diameter of 5 mm. The glass tube arrays are inserted into the *r*-*z* plane inside the vacuum vessel.

Table 1 compares several key parameters of conven-

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Table 1 Key parameters for conventional and PCB pickup coils.

	Conventional	PCB (Z-coils)
Coil size	5 × ϕ2 mm	5 × 3 × 1 mm
Number of coils for 2-D array	5 coils/12 cm	15 coils/15 cm
Coil density [cm^{-1}]	0.42	1
NS/RC [m^2/sec]	6.61 × 10^{-2}	1.15 × 10^{-2}
Standard error rate [%]	0.32	0.095

tional and PCB probe arrays for X-point structure measurement. The conventional arrays are composed of 60-channel pickup coils at spatial positions of 1, 2, 3, 5 cm in the z (current-sheet thickness) direction and 2, 4 cm in the r (current-sheet length) direction. The pickup coils made from 200-turn wires have lengths of 5 mm and diameters of 2 mm. However, their 1D arrays do not have sufficient space inside the thin (inner-side diameter 3 mm) glass because they require thick insulator jigs (mostly made from plastic) for accurate positioning and orientation, which is not the case for the thin and strong epoxy glass plates of PCBs. Thus, thin glass tubes can hold a larger number of PCB coils compared with conventional coils. The thin PCB coils have higher accuracy in coil positioning and orientation than conventional coils. A 2D PCB array is composed of a 75-channel probe whose coil circuit patterns are optimized for 2-cm resolution in the z-direction and 1-cm in the r-direction. The line density of PCB coil useful for closed flux detection is 1 cm^{-1}, which is about twice that of the conventional probe (0.42 cm^{-1}). Sensitivities of the PCB coil arrays have the standard deviation: 0.095% (n = 69), which is ∼1/3 of the conventional coil (0.32%; n = 58). This indicates that PCB coil calibration is not required. PCB probes are equipped with 5 × 3-mm^2 magnetic pickup coils. Each coil is composed of a two-sided (top of bottom) square coil pattern with a line width of 0.05 mm and a minimum line spacing width of 0.07 mm. Figures 1 (b) and (c) show the PCB coil circuit designs for three components of magnetic field B_x, B_y, and B_z. The number of turns and cross section of the coils were maximized to maximize sensitivity. For a compact feed-through area, a pair of twisted lead wires with diameters of 0.12 mm was soldered at the end of each coil pattern. In this study, 1D arrays solely with the PCB coil patterns for B_z (Fig. 1 (c)(iii)) were used to demonstrate the 10-mm resolution measurement of B_z in the first test. Under the assumption of toroidal symmetry, the 2D contours of the poloidal flux ψ were calculated from the B_z magnetic field profile measured at a single discharge.

Figures 2 (a) and (b) show the 2D poloidal flux contours of two merging ST plasmas, which are calculated from (a) conventional and (b) PCB probe data. These contours obtained from a single discharge were focused on their X-point areas for measuring detailed current-sheet structures from 814 to 816 µs. As shown in Fig. 2 (a), the contours measured by the PCB probe have small closed

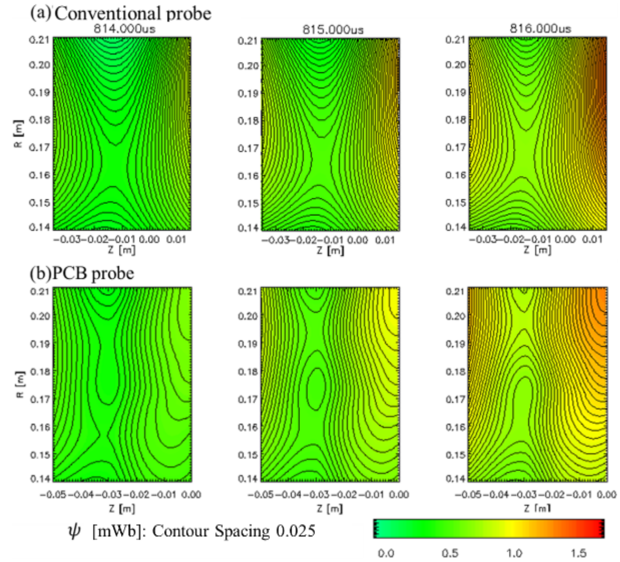

Fig. 2 2D poloidal flux contours of two merging ST plasmas measured by (a) the conventional pickup coil arrays and (b) the new PCB probe arrays.

fluxes around the X-point, indicating the formation of plasmoid. The plasmoid was clearly observed at 815 µs and ejected downward at 816 µs. In contrast, the contours measured by the conventional probe have simple X-point structures without plasmoid during reconnection. Since 2001, we have been reporting the current-sheet ejection during the merging of two ST plasmas. However, we could not find any closed flux inside the ejecting sheet [6] using the conventional probe array. The high-resolution measurement by the PCB coil array has enabled us to identify the plasmoid ejection for the first time during two tokamak merging.

In summary, we developed a high-resolution and highly accurate 2D magnetic field measurement system using a two-sided PCB coil pattern with a line width of 0.05 mm. Presently, PCB probe arrays realize spatial resolutions as high as 5 mm and their sensitivities have a standard deviation ∼1/3 that of the conventional coil. Using this new PCB probe, we measured detailed magnetic field structures of the current sheet in a TS-3U ST merging experiment and detected a magnetic island in push mode reconnection [3, 6] for the first time.

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