New toroidal magnetic probe arrays for non-axisymmetric magnetic perturbation measurements in KSTAR tokamak

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Recently, the results from the measurements of the plasma response to non-axisymmetric magnetic perturbation (NMP) fields by using magnetic sensors were reported in the DIII-D tokamak, and the NMP fields have been found to be beneficial in fusion energy relevant plasma studies [1-3].

The axisymmetric equilibrium magnetic field measurement by using one set of the poloidal magnetic probe (MP) array [4] was enough to be used for the plasma control during plasma discharges and the equilibrium reconstruction after plasma shots until the experimental campaign of 2014 in the KSTAR tokamak. However, the NMP measurement was also required in the KSTAR after achieving the ELM suppression by using resonant magnetic perturbation (RMP) coils [5]. Thus, new three toroidal MP arrays were installed at passive stabilizers (PSs) to measure the NMP at the low field side (LFS) during plasma discharges for investigating the plasma response to intrinsic and applied NMP field in the KSTAR. Figure 1 shows the toroidal MP arrays consisting of two and four pairs of sensors at the upper PS (‘MPZ#U03’ and ‘MPZ#U04’, respectively) and four pairs (‘MPZ#L20’) at the lower PS.

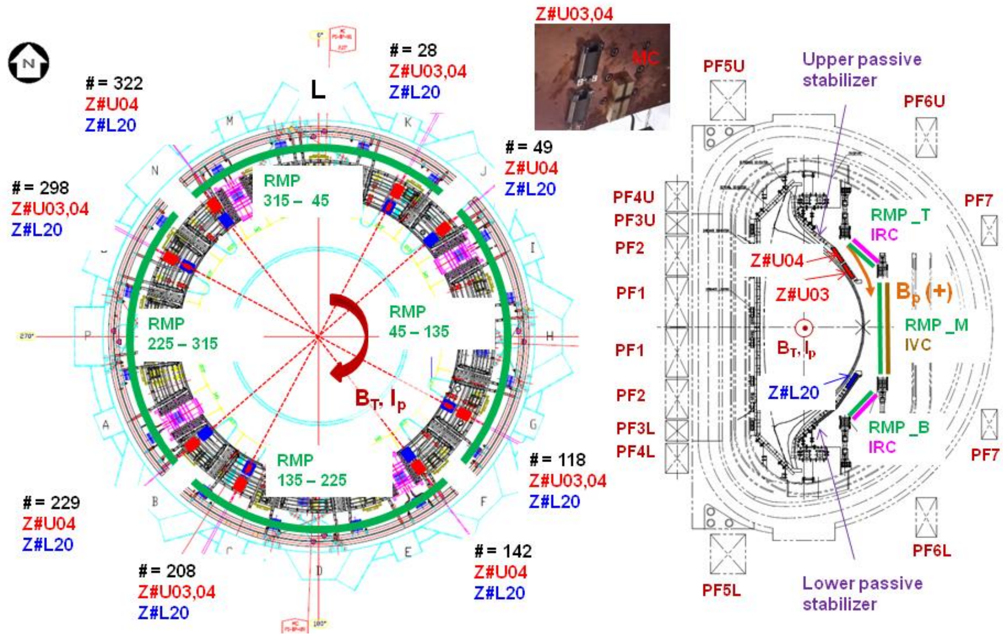

Fig. 1. Toroidal MP arrays for the measurement of the 3D field: top view (left side) and poloidal cross-sectional view (right side). Here, the toroidal angle is relative to the port L, and the value of the angle increases in the clockwise direction. The polarity of sensor signal is set as ‘+’ when the poloidal field is in the clockwise direction. These are just for convenience.

The pairs of two sensors were used to evaluate more clearly odd or even components in the NMP field at the LFS during plasma discharges. The difference of the toroidal angle between two sensors in each pair was 180 degrees. All of MPs in the toroidal array were installed at the backplates used for mounting the graphite tiles at the PSs, and were located at the position of ~ 1 cm behind the surface of the graphite tiles. There was the gap of 2 mm between two adjacent tiles, which was used as an opening for the better magnetic measurements. The effective areas of the MPs for measuring the tangential component of the poloidal magnetic field were calibrated as (6.2 - 6.7) × 10^{-2} m^2. The polarity of each MP was checked from the vacuum field measurement during the pulsed activation of the poloidal field (PF) coils or in-vessel radial control (IRC) coil for producing a vertical field. The length of the twisted paired signal cable (LEMO) from the vacuum feethroughs to the DAQ system for the MP was about 80 m. The analog integrator and digitizer (ACQ196CPCI-96 @D-tAcq) were used for the measurements. The sampling rate of the digitizer was 10 kHz. The *RC* time constant of the integrator was 10 ms. The digitizer sensitivity was 3.05 × 10^{-4} V/bit because the digitizer had the maximum input voltage of ± 10 V and the 16 bit resolution.

There were three different groups of magnet coils for producing the axisymmetric radial and vertical magnetic fields in the KSTAR as following; eleven independent superconducting PF coils and two independent normal copper in-vessel control (IC) coils consisting of the in-vessel vertical control (IVC) and IRC coils. In addition, the three different groups of RMP coils (top, middle and bottom) were used to produce the NMP field at the edge region: Four normal copper RMP coils in each group are equally distributed in the toroidal direction [5].

Fig. 2 shows one example of the field measurements during the RMP coil activations for the DC coupling coefficients between sensors and the RMP coils.

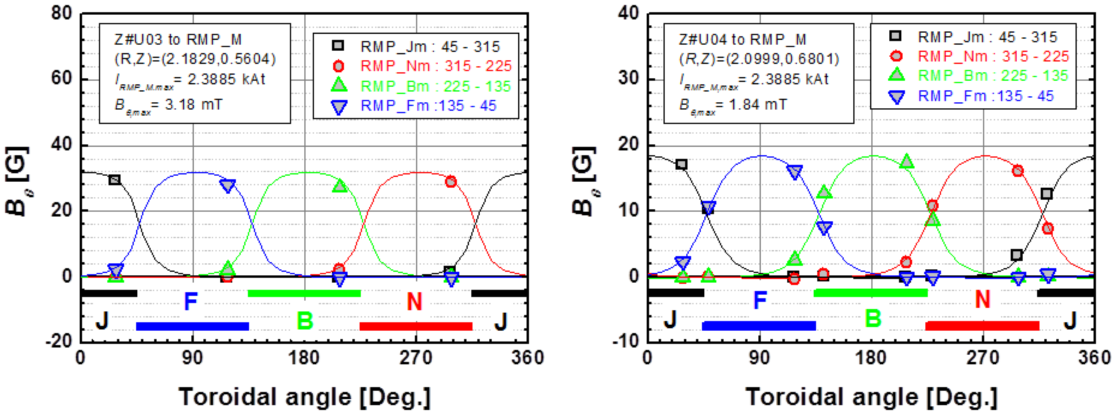

Fig.2. Toroidal distribution of poloidal magnetic field measured with the MP arrays: (a) MPZ#U03 and (b) MPZ#U04 when the pulsed current (~2.39 kAt) is applied to the middle RMP coils at the four different locations such as J-F, F-B, B-N, and N-J inside the KSTAR vacuum vessel.

The measurements agree well with the calculated values for the given geometries of the RMP coils and magnetic sensors within the discrepancy of 7 %. There was a similar trend in the measured values from the MPZ#L20. The DC vacuum coupling coefficient a_{ij} of each sensor to the each of the PF, the IC and the RMP coils was simply evaluated for the applied current I_j in the vacuum flux measurements by using $a_{ij} = < B_i >/< I_j >$. Here, $< B_i >$ and $< I_j >$ were the time-averaged values of the i-th sensor and the j-th coil current at the flat-top region, respectively. The DC coupling coefficients are summarized in Table 1.

Table 1. Vacuum DC coupling coefficients of MP .

Magnetic field coils	a_{ij} [G/kAt]	Remarks
PF coils	-20 ~ 230	PF1,PF2, PF3U(L) ~ PF6U(L), PF7
IC coils	-26 ~ 30	IRC, IVC coils
RMP_M coils	0 ~ 12	Middle
RMP_T coils	-6 ~ 4	Top
RMP_B coils	0 ~ 0.8	Bottom

Thus, the DC compensated magnetic field in the i-th sensor δB_i^{comp} can be obtained from the subtractions of the vacuum field pick-ups B_i^{vac} due to applied magnetic coil current I_j and the field B_i^{Ip} due to plasma current I_p by using the vacuum coupling coefficients a_{ij} and a_{iIp}, respectively as;

$$\delta B_i^{comp} = B_i - \left(B_i^{vac} + B_i^{Ip}\right) = B_i - \left(\sum_j^N a_{ij} I_j + a_{iIp} I_p\right) \tag{1}$$

Here, the value of a_{iIp} was less than ~ 1.3 G/MA obtained during a wall reference shot (0.6 MA). In addition, the differential signals from the paired sensors are used to detect clearly a small NMP field because the differential method can efficiently eliminate axisymmetric components in the sensor signal as

$$\begin{aligned} \delta B_{i,odd} &= \left(\delta B_{i,\Phi 1} - \delta B_{i,\Phi 1+180}\right)/2, \\ \delta B_{i,even} &= \left[\left(\delta B_{i,\Phi 1} + \delta B_{i,\Phi 1+180}\right) - \left(\delta B_{i,\Phi 2} + \delta B_{i,\Phi 2+180}\right)\right]/4 \end{aligned} \tag{2}$$

Where $\delta B_{i,\Phi}$ and $\delta B_{i,\Phi+180}$ are two DC compensated signals in a paired sensor.

The applicability of the MP array to the measurement of plasma response to the small 3D field was investigated for a natural mode locking. When the ramping rate dI_p/dt was sustained about 0.5 MA/s in the ramp-up phase of plasma current, the tearing mode (TM) of $m/n = 2/1$ appeared and the mode was naturally locked at a certain time during ohmic discharges with low density in the KSTAR. It can be clearly found from the differential sensor signal such that the mode is locked at ~0.832 s and its amplitude of mode locking is saturated at ~0.838 s, and plasma is eventually disrupted at 0.846 s as shown in Fig. 3(a). The mode locking can be also detected by using a Mirnov coil (MC) as shown in Fig. 3(b). The frequency f_{TM} of the TM (n = 1) decreases from ~1.8 kHz and becomes zero at 0.83 s where n is a toroidal mode number of the TM. The values of f_{TM} and n were identified from the spectrogram of the MCs. The experimental conditions in the time range of 0.5 – 0.84 s were following; toroidal field B_T = ~1.5 T, plasma elongation κ = ~1.2, I_p = 0.30 - 0.46 MA, plasma density n_e = (0.44 – 0.8) × 10^{19} m^{-3} and safety factor q_{95} = 2.9 – 2.3.

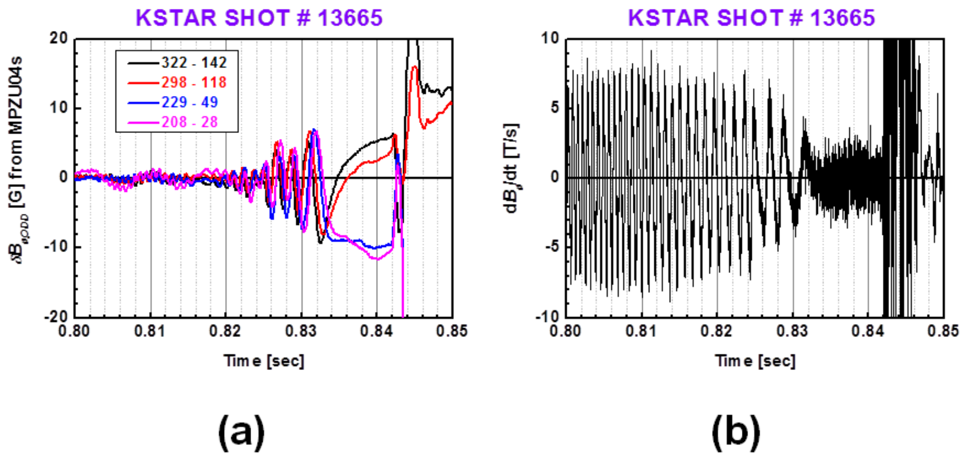

Fig. 3. Time evolutions of (a) differential signals presenting the odd components at four different toroidal locations, and (b) Mirnov coil signal when natural locking is occurred.

The preliminary work for the investigation of the plasma response to the NMP fields was carried out by using only DC compensated sensor signals from the new toroidal MP array measurements. For better investigation of the plasma response to the 3D field produced from the RMP coils, the AC coupling coefficients characterizing the frequency and phase will be evaluated to obtain the transfer functions between sensors and magnetic coils, which will used to compensate vacuum flux due to eddy current induced on the passive stabilizer when the top and bottom RMP coils will be activated during plasma discharges in the KSTAR. In addition, we will try to interpret qualitatively the poloidal structure of the NMP field from the three toroidal MP array measurements. This research was supported by Ministry of Science, ICT, and Future Planning under KSTAR project contract.

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