Poloidal iso flux during the transients of the KT-1 tokamak

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Without knowledge of the internal plasma current profile, the outmost poloidal iso flux surfaces are calculated by using a linear combination of the fields obtained during both the plasma current buildup and decay periods from measurements of the magnetic field at the plasma boundary of the KT-1 tokamak, where three different magnetic probes are arranged poloidally at 30 degree intervals outside the torus.

The equilibrium plasma is positioned at the geometrical center of the vacuum vessel by controlling the plasma position and shape with the help of a magnetic field in order to avoid severe energy loss or collapse of the plasma by minimizing the production of impurities [1–3]. The plasma current decay is caused mainly by the energy loss and the increase in the plasma resistance and leads to lost of plasma confinement or plasma disruption. There are several known causes of plasma disruptions [4]. As the duration time of the plasma gets longer, control of the cross-sectional plasma shape and of the magnetic field supplied by the external magnetic coils becomes more important and is being actively studied in several tokamaks with long flat-top periods [5–7]. Control of the plasma position by using external magnetic coils requires that information on the plasma position be given. Since the first introduction of theta coils to measure the plasma displacement by Mironov [8], magnetic probes, such as flux loops and sine and cosine coils, have been used in measuring and controlling the position and the cross-sectional shape of a tokamak plasma due to their versatility. A system for measuring and controlling the plasma position and shape consists of magnetic probes installed close to the plasma, analog operational circuits, and control circuits for the equilibrium magnetic-field current. Plasma control has been obtained with success in various tokamaks [9–11] by using magnetic probes to measure the poloidal flux differences between the top and the bottom reference positions and between the inboard and the outboard boundaries of the plasma. Lee and Oh [12] proposed a new method to calculate the outermost poloidal flux surface on an RTP tokamak and performed feedback control of the plasma position by using a PID (proportional-integral-differential) controller. They compared the results obtained by using the PID controller with those obtained by controlling the current center of the plasma. Oh et al. [13] developed
a control system for the KT-1 tokamak and performed feedback control of the plasma position and current by using two saddle loops and one Rogowskii coil. They showed an improvement in the plasma performance without knowing the exact position of the plasma. As an another improvement of their work, a method to calculate the exact position of a plasma during the equilibrium period of KT-1 plasmas has been introduced [14]. Although the purpose of controlling the plasma position and shape is to avoid disruptions and to decrease impurities, these are most unlikely to happen during the equilibrium (current flat-top) period; rather, these are more likely during transient periods, such as current buildup and/or decay. As the mechanical and the physical limits of present and future tokamak devices become stricter, it should be determined the number of operations, or number of shots, so the necessity of avoiding disruptions has become more critical than ever. It is important and necessary to observe the exact position and shape of plasmas during these critical transient periods, and that is the purpose of this brief communication. In this work, the outmost poloidal iso flux surfaces of the KT-1 tokamak during both current buildup and decay periods are calculated for the first time as an improvement on our previous work [14], because the latter treated only equilibrium plasmas.

The KT-1 tokamak (major radius of 27 cm and minor radius of 5 cm) is operated with a feedback control system which controls ohmic heating (OH) and the vertical and the horizontal magnetic fields by using signals from a Rogowskii coil and from two saddle-loop coils, both 0-180 degrees and 90-270 degrees, located poloidally outside the vacuum vessel [13]. All magnetic-probe coils are arranged poloidally at 30 degree intervals. The magnetic probes are composed of 12 saddle-loop coils, 12 rho coils, and 12 theta coils. The toroidal (Ø) span of the saddle-loop coils is ΔØ = 30 degree. The theta coils, with a constant number of turns, are arranged from 0 degree to 270 degrees to measure the magnetic field in the θ (poloidal)-direction, and the rho coils, with a constant number of turns, are arranged from 15 degrees to 345 degrees to measure the magnetic field in the ρ (radial)-direction. Each theta coil is separated by 15 degrees from a rho coil. The saddle loops are one-turn coils arranged with different areas on the torus surface. All signals from the magnetic probes are measured simultaneously by using 36-channel VXI (VMEbus eXtensions for Instrumentation) digitizers (maximum 20 Ms/sec). The positions of the magnetic probes are \( r_M \) (radial position of the saddle-loop coils) = 5.8 cm, \( r_p \) (radial position of the plasma boundary) = 4.2 cm, and \( r_\theta \) (radial position of the theta and the rho coils) = 6.2 cm. Noises from outside the probes are minimized by using twisted signal lines and grounded, meshed copper-wire wrapped around the outside of all the signal lines bundled in one cable. The toroidal span and the equipartitional poloidal angle of the saddle-loop coils are both 30 degrees. The raw differential signals from 24 magnetic probes and 12 saddle loops are measured simultaneously through differential input channels by using 36-channel VXI digitizers. These data are integrated in a PC by using a FORTRAN program. The off-set values and the noises of the raw data are compensated for before integrating the data. The contour of the iso flux surface obtained from curve fitting is compared to
the plasma displacement measured from the 0-180 degree and the 90-270 degree saddle-loop signals used for feedback control of the plasma current because the latter show the position for the outermost flux surface of the plasma.

![Diagram of plasma and magnetic field](image)

**FIG. 1.** Coordinate system and characteristic variables in a KT-1 tokamak with the following parameters: major radius \( R = 27 \text{ cm} \), minor radius \( a = 5 \text{ cm} \), toroidal magnetic field \( B = 1 \text{ Tesla} \), \( \rho = \text{radial coordinate} \), \( \theta = \text{poloidal coordinate} \), and \( \phi = \text{toroidal coordinate} \).

While the calculation of the central position of the plasma current requires complex steps due to the Coulomb logarithm \((\ln \Lambda)\) and the distribution of the plasma current, the calculation of the outermost magnetic-flux surface needs neither a Coulomb logarithm nor compensation for the current induced on the vacuum vessel. Consequently, that calculation is very simple, and the only thing remaining to do is to correct the values measured at the plasma boundary because the positions of the magnetic probes do not coincide with the plasma boundary. To determine the poloidal flux at the plasma surface, we use the following equation for a given \( \theta \)-direction in the poloidal coordinate of a toroidal geometry:

\[
\Psi(\rho_p, \theta) - \Psi(\rho_M, \theta) = 2\pi \int_{\rho_M}^{\rho_p} (R + \rho \cos \theta) B_\theta(\theta, \rho) d\rho,
\]

where \( \rho_p \) and \( \rho_M \) are the radial positions of the limiter (plasma boundary) and a saddle loop, respectively [12]. The coordinate system and the position variables are shown in Fig. 1. Using the magnetic flux calculated from a second-order expansion of the measured flux and approximating \( B_\theta(\rho, \theta) \) as a linear function of \( \rho \) around \( \rho_p \) (positions of the poloidal-field pick-up probes, theta and rho coils), we obtain the flux difference between the \( \theta_i \)- and the \( \theta_j \)-poloidal directions as

\[
\delta \Psi_{ij} \equiv \Psi_{\rho_i} - \Psi_{\rho_j}
\]
\[
= (\Psi_{M_i} - \Psi_{M_j}) - (A_i B_{\theta i} - A_j B_{\theta j}) + \left(C_i \frac{\partial B_{\phi i}}{\partial \theta} - C_j \frac{\partial B_{\phi j}}{\theta}\right) - \mu_0 (b_i J_{\phi i} - b_j J_{\phi j}) - \frac{1}{c^2} \frac{\partial}{\partial t} (b_i E_{\phi i} - b_j E_{\phi j}),
\]

where
\[
\Psi_{p i} = \Psi(\rho_p, \theta_i), \quad \Psi_{M i} = \Psi(\rho_M, \theta_i), \quad B_{\theta i} = B_0(\rho_0, \theta_i), \quad B_{p i} = B_p(\rho_p, \theta_i), \quad J_{\phi i} = J_p(\rho_p, \theta_i), \quad E_{\phi i} = E_p(\rho_0, \theta_i), \quad A_i = a_i - (b_i/\rho_0), \quad C_i = -(b_i/\rho_0), \quad a_i = a_{p i}, \quad \text{and} \quad b_i = b_{\theta i} \equiv 4\pi e_i (h - e_i) (R + \rho_M \cos \theta_i).
\]

If the effects of the toroidal geometry are neglected for a well-controlled plasma, the plasma position displacement at \( \theta_j \), defined as \( \Delta e_j \), satisfies the equation
\[
\Psi_{p i}(e_i) - \Psi_{p j}(e_j = e_i + \Delta e_j) = 0, \quad e_j = \left(\frac{\rho_M - \rho_p}{2}\right) + \Delta e_j
\]

for a referenced plasma boundary position, \( \rho_{p i} \), since the poloidal-flux function satisfies \( \delta \Psi_{M_j} = 0 \) on the iso-flux surface. From the above equations with a Taylor expansion around \( e_j = e_i \), the plasma position displacement at \( \theta_j \), \( \Delta e_j \), is calculated as
\[
\Delta e_j = \frac{-\delta \Psi_{M j}(e_i = e_j)}{4\pi (U_j B_{\theta j} - V_j \frac{\partial B_{\phi j}}{\partial \theta})},
\]

where \( U_j = R(2 - \rho_p/\rho_b) + \rho_M (1 + \rho_p/\rho_M - \rho_p/\rho_b) \cos \theta_j, \quad \text{and} \quad V_j = (1 - \rho_p/\rho_b) (R + \rho_M \cos \theta_j) \), which indicates that \( \Delta e_j \) is very small in the region \( (\Delta e_j/\rho_b) \ll 1 \). Therefore, using the above equations and the values measured using the magnetic probes, we can calculate the outermost poloidal iso-flux surface displacement.

Figure 2 shows the loop voltage and the plasma current for typical KT-1 tokamak operation; 6 points were arbitrarily chosen for the analysis. The variations of the iso-flux surfaces during the buildup, the flat-top, and the decay periods of the plasma current at a radial position of 5.8 cm (radial position of the saddle-loop coils) are shown in Fig. 3. The flux surface line during the flat-top period in the figure indicates the time from the start of the current build up to the end of the flat-top. Figure 4 shows the result at the radial position of the plasma boundary (r = 4.2 cm). The central position of the iso-flux surface does not initially coincide with the geometrical center, and the initial shape is not circular. With increasing plasma current, the position of the iso-flux surface moves toward the geometrical center, and the shape becomes circular within circular limiters as the result of an equilibrium which is formed by a balance between the poloidal pressure and the radial magnetic force. During the decay of the plasma current and before disruption, the position and the shape of the iso-flux surface do not change much, while those during the current buildup period do. From this, one knows that the plasma gradually becomes stable during the buildup period, although the initial position and the shape are neither at the center nor circular. The shape and the position do not change much during the decay before plasma disruption due to the total consumption of volt second (flux swing) from the iron-core. A small horizontal displacement of the plasma position from the central position is shown.
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outward along the major radius of the KT-1 tokamak during the whole period. In order to compensate for this displacement, we must increase the vertical magnetic fields so as to move the plasma center to the geometrical center and to minimize contacts between the plasma and the inner surface of the vacuum vessel. These results will lead to future improvements in the confinement of plasmas in the KT-1 tokamak through the use of a more suitable and precise feedback control system.

FIG. 2. Loop voltage and plasma current at 6 time-points during the transient time.

FIG. 3. Variations of the isoflux surfaces during the buildup, the flat-top, and the decay periods of the plasma current at the radial position of the saddle-loop coils ($r = 5.8$ cm).
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REFERENCES

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JIPP T-II Tokamak," IPPJ-441 (Institute of Plasma Physics, Nagoya, Japan, 1980).


Res. 4, 10 (1999).