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Calculation of Plasma Position and Shape in KT-1 Tokamak

Doo-Hee Chang and Kyu-Sun Chung

Hanyang University
17 Haengdang-dong, Sungdong-gu, Seoul 133-791, Korea

Byung-Hoon Oh, Seung-Ho Jeong, Bong-Guen Hong, Kwang-Won Lee,
Sung-Kyu Kim, and Byung-Ho Choi

Korea Atomic Energy Research Institute
150 Dukjin-dong, Yousung-gu, Taejeon P.O.Box 105, Korea

Abstract

For the first time, the full-time scale variations of plasma position and shape from the outmost poloidal isoflux surfaces during the buildup, flat-top, and decay period of plasma current are calculated from the measurement of magnetic fields at the plasma-boundary surface in a KT-1 tokamak (major radius of 27 cm and minor radius of 4.2 cm). Three kinds of magnetic probes arranged poloidally in 30 degrees outside the torus are used in determining the plasma boundary. Without the information of internal plasma current profiles, the calculations are only performed by a linear combination of measured fields.

1. Introduction

If the equilibrium of tokamak plasma around the center of vacuum vessel and the separation of main core plasma from the wall surface of tokamak device are not maintained during the operational period, then the generation of impurities from the plasma facing components (PFCs) will lead to the severe energy loss or collapse of plasmas.[1-3] In order to minimize the production of impurities, the plasma in equilibrium state should be positioned inevitably at the geometrical center of vacuum vessel by controlling the plasma position and by shaping it with the measurement of magnetic fields, which maintains the equilibrium of tokamak plasma in time by changing the inner pressure and plasma current profiles, in the main core plasma. As the duration time of the plasma gets longer, the control of cross-sectional plasma shape and of magnetic field supplied by external magnetic coils become more important and is being actively studied in several tokamaks with a long flat-top period.[4-6] The plasma current decay is caused mainly by the energy loss and the increase of plasma resistance, and it leads to break the plasma confinement or plasma disruption. There are several well-known causes of plasma disruptions.[7] Although the purpose of controlling the plasma position and shape is to avoid the disruption and to decrease the impurities, these are most unlikely to happen during the equilibrium (current flat-top) period, rather these are more susceptible during the transient periods such as current buildup and/or decay. As the mechanical and physical limits of present and future tokamak devices becomes more strict, they decide the number of operations or shot numbers, so that the necessity of avoiding the disruption is becomes more critical than ever. It is important and necessary to observe the exact position and shape of plasmas during these critical transient periods. Although magnetic probes cannot measure the spatial variations of the inner plasma, they have been used both in measuring and controlling the position and the cross-sectional shape of a tokamak plasma due to their simplicity, reliability, and robustness. The 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. Lee and Oh[8] proposed a new method to calculate the outermost poloidal flux surface on a RTP tokamak (major radius of 72 cm and minor radius of 18 cm) and performed the feedback control of plasma position by using PID (Proportional-Integral-Differential) controller. They compared the results obtained by PID controller with those by controlling the current center of plasma. Analog integrators have been used for the integration of signals from the magnetic probes on a RTP. Oh et al.[9] developed a control system for the KT-1 tokamak and performed the feedback control of plasma position and current in the KT-1 tokamak by using saddle loops and Rogowski coils. They resulted in an improvement for the plasma performance without knowing the exact position of the plasma. In order to improve their method, one has to know the exact poloidal magnetic flux surface. In this work, the outmost poloidal isoflux surfaces of the KT-1 tokamak are calculated during the current buildup, flat-top, and decay period, for the first time, in the KT-1 tokamak as an improvement of our previous work[10] since the result treated only for the equilibrium plasmas during the current flat-top period. We calculate the exact position of the KT-1 plasma as an improvement of the work of Oh, et al. We install all the magnetic probes outside the vacuum vessel and add B_θ coils as a refinement of the work from Lee and Oh. While the magnetic probes, except the saddle loops, are located inside a vacuum vessel in a RTP, all the magnetic probes, including the saddle loops, are located outside a vacuum vessel in the KT-1. In our experiment, the differential signals from the magnetic probes were obtained directly from the digitizers and were integrated in a personal computer (PC) for calculations afterwards in order to minimize any additional device errors. We adopt Lee's method which is used in the RTP tokamak.

2. Experiments

The KT-1 tokamak (major radius of 27 cm, minor radius of 4.2 cm, inner radius of torus surface of 5 cm) is operated with a feedback control system, which controls the ohmic heating (OH), the vertical, and the horizontal magnetic fields by using signals from a Rogowski coil and from two saddle-loop coils, both 0-180 degree and 90-270 degree, located poloidally outside the vacuum vessel.[9] All magnetic probe coils are arranged poloidally in 30 degrees. The magnetic probes are composed of 12 saddle-loop coils, 12 rho coils, and 12 theta coils. The toroidal(ϕ) span of the saddle-loop coils, which are one-turn coils arranged with different areas on the torus surface, is $\triangle\phi$ = 30 degree. The theta coils, which are separated in 15 degrees from a rho coil, are arranged with a constant number of turns from 0 degree to 270 degrees to measure the magnetic field in the θ (poloidal)-direction, and the rho coils are arranged with a constant number of turns from 15 degrees to 345 degrees to measure the magnetic field in the ρ-direction. All signals from the magnetic probes were measured simultaneously by using 36-channel VXI (VMEbus eXtensions for Instrumentation) digitizers (maximum 20 Ms/sec). The results of flux surface calculation in this experiment were compared to the signals from the two saddle-loop coils (0-180 degree and 90-270 degree coils) used for the current feedback control. The position of current in the KT-1 plasma is controlled by the feedback control of vertical and horizontal magnetic fields, which are calculated by the signals of two saddle loops located from 0 to 180 degree and from 90 to 270 degree.[12] The calculations of poloidal isoflux surface were performed by using a linear combination of measured fields. Saddle loops and magnetic probes are installed poloidally outside the vacuum vessel of the KT-1 tokamak. Two stainless steel poloidal limiters with the thicknesses of 8 mm are located inside the vacuum vessel and are separated by 180 degrees in the toroidal direction, which makes the radius of real boundary for the plasma column as 4.2 cm. The position of magnetic probes are ρ_M (radial position of the saddle-loop coils)=5.8 cm, ρ_p (radial position of the plasma boundary)=4.2 cm, and ρ_b (radial position of the theta and rho coils)=6.2 cm. The maximum area of a saddle loop is 52 cm^2, and that loop is located at poloidal angle of 0°. The minimum area is 34 cm^2, that loop is located at 180 degrees. The total areas of theta and rho coils are both 17.6 cm^2, which is the number of turns times the effective area of one turn. Noise from outside the probes is minimized with twisted signal lines and grounded-meshed copper wire wrapped around the outside all the signal lines bundled in one cable. The toroidal span and the equipartitional poloidal angle of saddle-loop coils are all 30 degree. Raw signals from 24 magnetic probes and 12 saddle loops were measured simultaneously by using 36 channels of VXI digitizers through the differential channels. These data are integrated by using a FORTRAN program in a PC. The off-set values and the noises of raw differential data from the magnetic probes are compensated before integrating the data. The most significant noises come from the pick-up signals of toroidal magnetic fields, which seem to be due to the misalignment of the magnetic probes. To obtain a smooth contour, we obtain values at 360 points(one point per degree) from 12 measured points by using the polynomial curve fitting. The final contour of the isoflux surface obtained from the calculation through curve fitting is compared to the plasma displacement measured from the 0-180 and the 90-270 saddle-loop signals used for the feedback control of the plasma current because the latter show the position for the outermost poloidal flux surface of the plasma.

3. Analysis

While the calculation of central position in the plasma current requires complex steps due to the Coulomb logarithm ($\ln\Lambda$) with the distribution of plasma current, the calculation of outermost poloidal magnetic flux surface needs neither such Coulomb logarithm nor compensation for the current induced on a vacuum vessel. This is very simple compared to the current center method. 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 well with the plasma boundary. To determine the poloidal flux at the plasma surface, the following equation is used for a given θ (poloidal)-direction:

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

where ρ_p and ρ_M are the radial positions of the limiter and a saddle loop, respectively.[8] The coordinate system and position variables are shown in Fig. 1. By means of the magnetic flux calculated by a second-order expansion of measured flux and the approximation of

$B_\theta(\rho, \theta)$ as a linear function of ρ around ρ_b (position of a poloidal field pick-up probe, theta and rho coils), the flux difference between the θ_i- and the θ_j-poloidal directions can be obtained as

$$\delta\Psi_{ij} = \Psi_{pi} - \Psi_{pj}$$

$$= (\Psi_{Mi} - \Psi_{Mj}) - (A_i B_{\theta i} - A_j B_{\theta j}) + \left(C_i \frac{\partial B_{\rho i}}{\partial \theta} - C_j \frac{\partial B_{\rho j}}{\partial \theta}\right) - \mu_0 (b_i J_{\phi i} - b_j J_{\phi j})$$

$$- \frac{1}{c^2} \frac{\partial}{\partial t} (b_i E_{\phi i} - b_j E_{\phi j}),$$

where $\Psi_{pi} = \Psi(\rho_p, \theta_i)$, $\Psi_{Mi} = \Psi(\rho_M, \theta_i)$, $B_{\theta i} = B_\theta(\rho_b, \theta_i)$,

$B_{\rho i} = B_\rho(\rho_b, \theta_i)$, $J_{\phi i} = J_\phi(\rho_b, \theta_i)$, $E_{\phi i} = E_\phi(\rho_b, \theta_i)$,

$a_i = a_{\theta i}$, $b_i = b_{\theta i} \cong 4\pi e_i (h - e_i)(R + \rho_M \cos\theta_i)$,

$A_i = a_i - (b_i/\rho_b)$, and $C_i = -(b_i/\rho_b)$.

Neglecting the effects of toroidal geometry for the well-controlled plasma, the plasma position displacement, defined as $\triangle e_j$, at θ_j satisfies the equation

$$\Psi_{pi}(e_i) - \Psi_{pj}(e_j = e_i + \triangle e_j) = 0, \quad e_j = \left(\frac{\rho_M - \rho_p}{2}\right) + \triangle e_j$$

for a referenced plasma boundary position, ρ_{pi}, since the poloidal flux function satisfies $\delta\Psi_{Mij} = 0$ on the isoflux surface, From the above equations with Taylor expansion at $e_j = e_i$, the plasma position displacement $\triangle e_j$ at θ_j is calculated as

$$\triangle e_j = \frac{-\delta\Psi_{Mij}(e_i = e_j)}{4\pi \left(U_j B_{\theta j} - V_j \frac{\partial B_{\rho j}}{\partial \theta}\right)},$$

where $U_j = R(2 - \rho_p/\rho_b) + \rho_M(1 + \rho_p/\rho_M - \rho_p/\rho_b)\cos\theta_j$,

and $V_j = (1 - \rho_p/\rho_b)(R + \rho_M \cos\theta_j)$, which indicates that $\triangle e_j$ is a very small value in the region of $(\triangle e_j/\rho_b) \ll 1$.

4. Results and Conclusions

The outermost poloidal isoflux surface of the KT-1 tokamak are calculated during the buildup, flat-top, and decay period of plasma current as a function of time variation by using the magnetic fluxes measured by 12 saddle loops and 24 magnetic probes (12 theta and 12 rho probes) arranged poloidally in 30 degrees outside the vacuum vessel. All the data from probes are received by using 36 channels of VXI digitizers simultaneously and are integrated with a computer program to minimize the errors from the additional analog devices. The typical data for the loop voltage, the plasma current, and the signals from two saddle loops on the KT-1 tokamak are shown in Fig. 2. Occasionally, plasma disruption occurs at the end of the plasma discharge. The signal from the saddle 90-270 probe shows that vertical displacement of the plasma position from the geometrical center does not occur during the current feedback control, while that from the saddle 0-180 probe shows that the horizontal displacement of the plasma position from the central position is shifted outward along the major radius by the Grad-Shafranov shift[11], although current feedback control is maintained.[9]

This shows that the plasma position does not move vertically, but shifts horizontally in the outward direction along the major radius. Also, the plasma position and shape do not change severely during the present current feedback control. The contour plots of isoflux surfaces during the current buildup, flat-top, and dacay period at the radial position of 4.2 cm and 5.8 cm in poloidal geometry are shown in Fig. 3 and Fig. 4, respectively, with the torus position. This result coincides with the results from the output signals of the two saddle loops as a result of the feedback control of the plasma current. The central position of isoflux surface is initially not coincide with the geometrical center, and the initial shape is not circular, either. With increase of plasma current, the position of isoflux surface moves to the geometrical center, and the shape becomes circular within circular limiters as the result of an equilibrium formed by the balance between the poloidal pressure and radial magnetic force. During the decay of plasma current and before disruption, the position and shape of isoflux surface are not changed much, while those during the current buildup and flat-top period. From this, one knows that plasma gradually becomes stable during the buildup period, although the initial position and shape are neither at the center nor circular. Shape and position are not changed much during the decay before plasma disruption due to the total consumption of volt-second from iron-core. A little horizontal displacement of the plasma position from the central position is shown outward along the major radius of the KT-1 tokamak during the whole period. In order to compensate this displacement, more vertical magnetic fields should be supplied to move the plasma center to the geometrical center and to minimize the contacts between the plasma and inner surface of vacuum vessel. These results will improve the confinement of the plasma in the KT-1 tokamak with a more suitable and precise feedback control system in the future.

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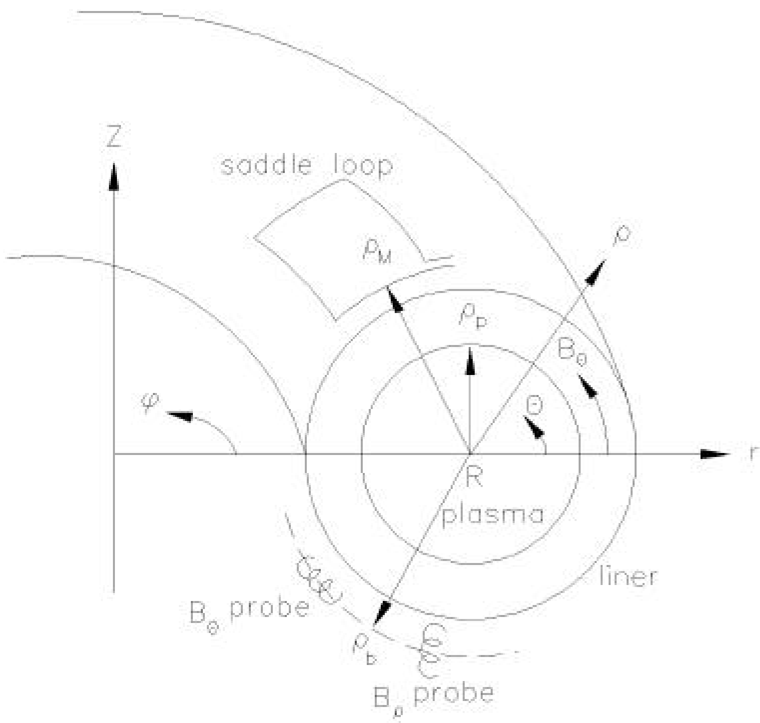

B_Θ : poloidal field
R : geometrical center of the liner

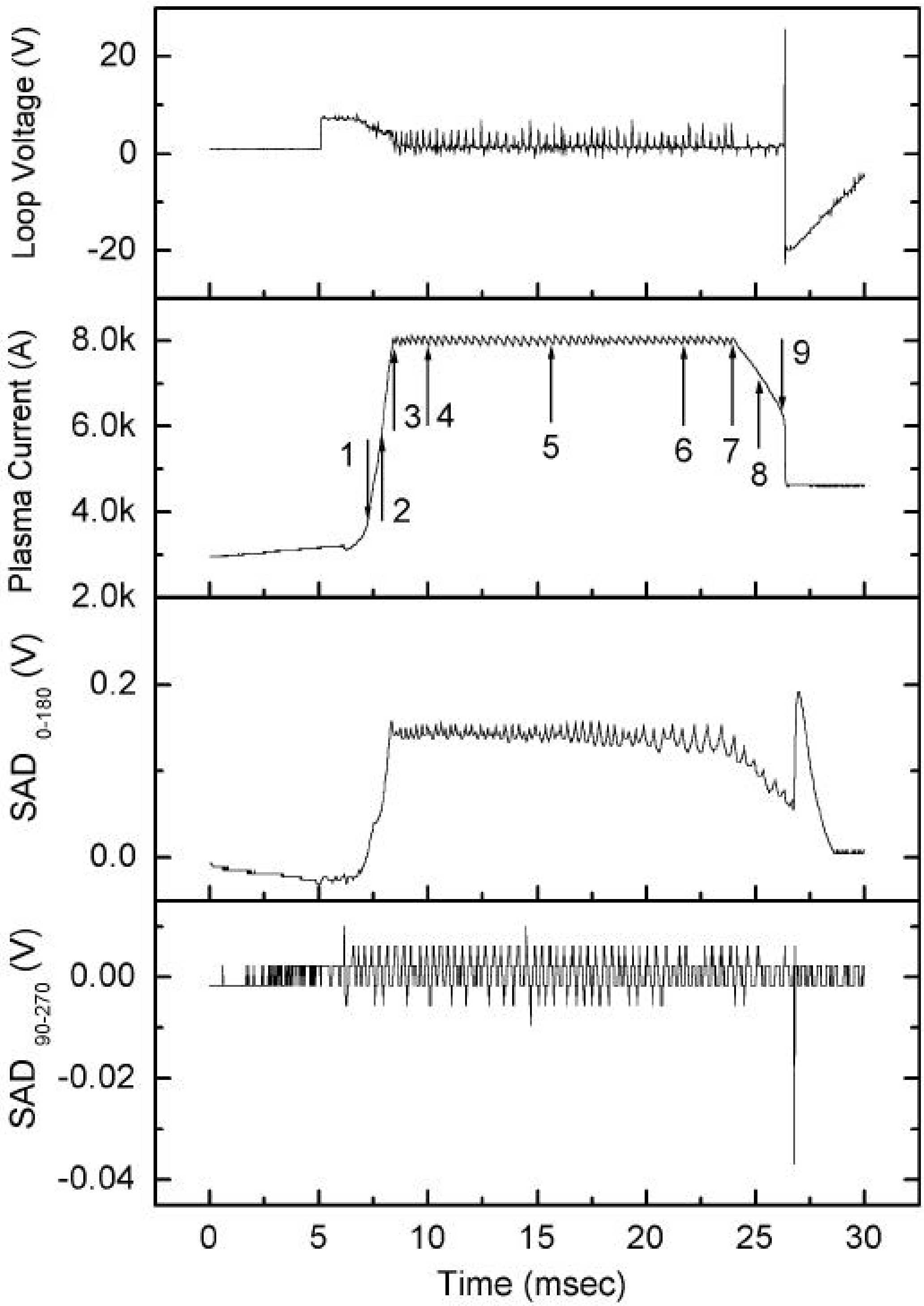

Fig. 2. Loop voltage, plasma current, and signals from two Saddle loops with a half circle.

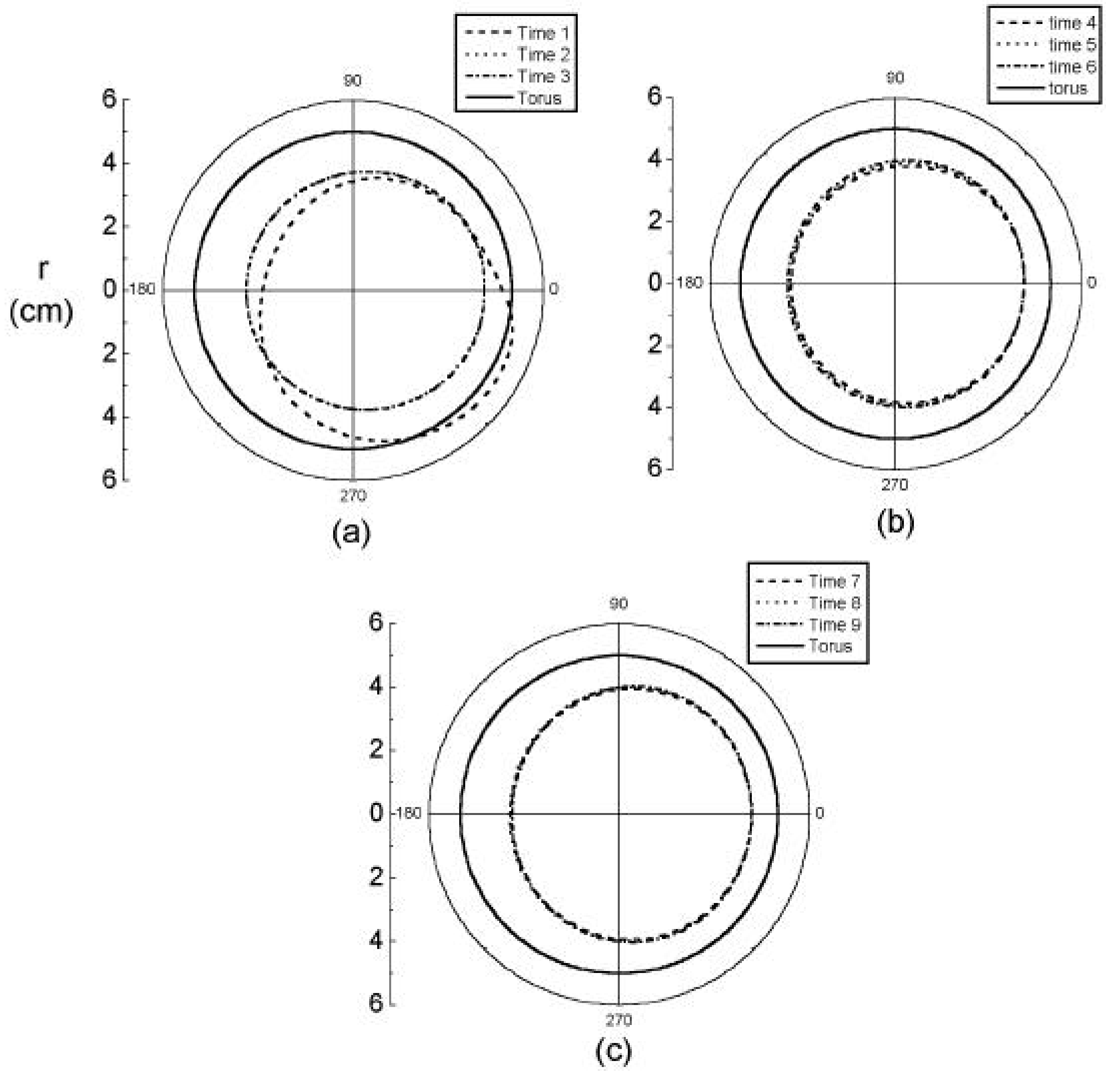

Fig. 3 Contour plots of isoflux surfaces during the current buildup (a), flat-top (b), and dacay

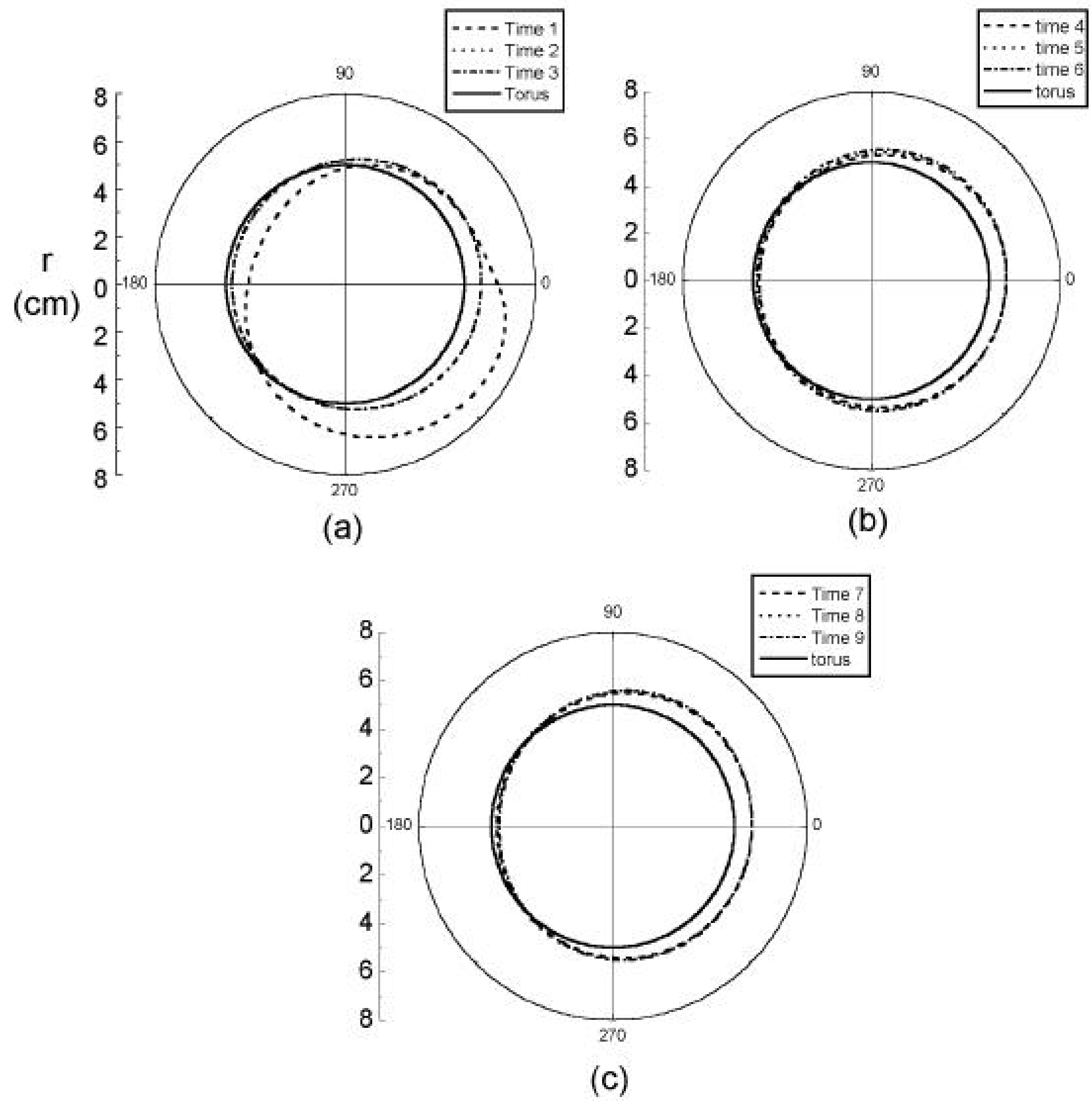

Fig. 4 Contour plots of isoflux surfaces during the current buildup (a), flat-top (b), and dacay (c) period at the bondary position of 5.8 cm in poloidal geometry