Off-axis Current Drive and Current Profile Control in JT-60U

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Abstract. Aiming at optimization of current profile in high-\(\beta\) plasmas for higher confinement and stability, a real-time control system of the minimum of the safety factor (\(q_{\text{min}}\)) using the off-axis current drive has been developed. The off-axis current drive can raise safety factor in the center and help to avoid instability that limits performance of the plasma. The system controls injection power of lower-hybrid (LH) waves, and hence, its off-axis driven current in order to control \(q_{\text{min}}\). The real-time control of \(q_{\text{min}}\) is demonstrated in a high-\(\beta\) plasma, where \(q_{\text{min}}\) follows the temporally changing reference \(q_{\text{min,ref}}\) from 1.3 to 1.7. Applying the control to another high-\(\beta\) discharge (\(\beta_N=1.7,\ \beta_P=1.5\)) with \(m/n=2/1\) neo-classical tearing mode (NTM), \(q_{\text{min}}\) was raised above 2 and the NTM was suppressed. The stored energy increased by 16 % with the NTM suppressed. For the future use for current profile control, current density profile for off-axis neutral beam current drive (NBCD) is for the first time measured, using motional Stark effect (MSE) diagnostic. Spatially localized NBCD profile was clearly observed at the normalized minor radius \(\rho\) of about 0.6-0.8. The location was also confirmed by multi-chordal neutron emission profile measurement. The total amount of the measured beam driven current was consistent with the theoretical calculation using the ACCOME code. The CD location in the calculation was inward-shifted than the measurement.

1. Introduction

Development of advanced scenario is required in the realization of the future fusion reactor having high confinement and high stability in the core plasma. Actually, in the international thermonuclear experimental reactor (ITER), two advanced scenarios have been proposed, i.e. hybrid operation and steady-state operation scenarios. Candidates for the scenarios can be either a positive-shear or reversed-shear plasma, respectively. It is well known that the current profile in both the positive-shear and reversed-shear plasmas plays important roles in confinement and stability. Thus, optimization of the current profile (or the safety factor (\(q\)) profile) is essential in developing such advanced scenarios.

The optimization of the current profile means control of the current profile. In a long-pulse operation aiming at the steady-state operation for fusion reactor, pre-programmed control of external current drivers is not enough for current profile control, since plasma must experience various stages having different confinement and bootstrap current profile, such as current ramp-up, H-mode transition and internal-transport-barrier formation. Thus, current profile control in ‘real-time’ during the discharge is required. In 2004, JT-60U demonstrated the real-time control of current profile at low-\(\beta\) L-mode discharges [1]. In such a low \(\beta\) condition, plasma can be MHD-stable and change in pressure, and hence change in bootstrap current is small. Driven current can be sufficiently large in the low-density condition, in order to modify current. The situation dramatically changes in a high-\(\beta\) plasma. An MHD instability degrades confinement, and affects the pressure profile and the bootstrap current having large portion of plasma current (\(I_p\)). High-density condition reduces externally driven current at a given power of current driver. More importantly, in order to sustain the high-\(\beta\) plasma, such MHD instability should be avoided or stabilized through optimization of current profile. Since external current drive power is limited due to some economic (reduction of circulating power in a plant) or technical reasons (equipment of current drivers), smaller control is better. Thus, JT-60U has proceeded to the real-time current profile control in a high-\(\beta\) plasma, the challenging study. Since low \(q\) rational surface usually plays harmful role, such as in the sawtooth oscillation and in the neo-classical tearing mode (NTM), control of the minimum of...
safety factor ($q_{\text{min}}$) is effective in order to eliminate the MHD resonant rational surface.

In the optimization of the current profile, some external current drivers must modify current profile, in combination with inherent inductive and bootstrap currents. There are two promising on-axis current drivers, neutral beam current drive (NBCD) and electron cyclotron current drive (ECCD). The on-axis NBCD was already investigated in detail on JT-60U [2,3]. The on-axis ECCD was also studied well in JT-60U [4,5] and in DIII-D [6,7]. On the other hand, off-axis current drivers would be lower-hybrid current drive (LHCD) or NBCD. Although it is difficult to drive current off-axis, where electron temperature, and hence, current drive efficiency is low, optimization of current profile needs a reliable off-axis current driver. Moreover, the off-axis NBCD is taken under consideration in JT-60SA for the control of current profile and for the formation and sustainment of reversed-shear plasmas [8]. Although the LHCD was studied well in various devices including JT-60U [9,10], study on the off-axis NBCD is still under way. Although the off-axis NBCD has been successfully used in JT-60U experiment in order to modify current profile, detailed measurement of the off-axis NBCD “profile” has not yet been done. Since the importance of the off-axis current drive has increased from the viewpoint of realization of the real-time current profile control, and since improvement in MSE system in JT-60U has made the measurement of NBCD profile possible, we address here the investigation of the off-axis NBCD. In ASDEX-Upgrade [11], change in pitch angles of an MSE diagnostic induced by the off-axis NBCD was compared to simulations. They found the change was smaller than the ASTRA simulation. Later, they reported that the change agrees with ASTRA/TRANSP simulation under a certain heating power criterion or assumption of fast-ion diffusion [12,13], but in some cases, the off-axis NBCD did not show change in the pitch angles compared to the on-axis NBCD [12,13]. Thus, understanding of the off-axis NBCD is tangled. We investigate the off-axis NBCD here, exploiting a newly developed analysis technique [14] to evaluate small change in current profile from MSE [15] and newly equipped neutron emission profile diagnostic [16].

Section 2 describes various current drivers in JT-60U. Real-time control of current profile by off-axis LHCD in a high-$\beta$ plasma is demonstrated in section 3. Section 4 is assigned to investigation of off-axis NBCD in detail for future use as a current driver.

2. Current drivers in JT-60U

JT-60U is equipped with various current drivers, NBCD, LHCD, and ECCD. Here, current drivers used in this study (NBCD and LHCD) are briefly explained. JT-60U has 11 units of neutral beam injectors based on positive ion source (P-NBI [17]) and one unit of neutral beam injector based on negative ion source (N-NBI [18]). Injection energies of the P-NBI and N-NBI are 80-85 keV and 300-400 keV, respectively. Injection powers of the P-NBI and N-NBI are 2-2.5 MW and 5-7 MW per one unit, respectively. The injection energy and power depend on pulse length of injection. P-NBI and N-NBI have two ion sources (A and B) in each unit. Figure 1 shows the poloidal cross section of JT-60U with NB trajectories. Two of 4 tangential P-NBIs are on-axis and the others are off-axis, in usual magnetic configuration in JT-60U. One of the two on-axis or two off-axis P-NBIs is injected to co-direction to the plasma current, and the others are to counter-direction for co-counter current drive, respectively. The other seven P-NBIs are injected...
almost perpendicular to the toroidal direction so that no effective NBCD is possible. Four of the seven P-NBIs injected from upper outboard are for on-axis heating, and the other three P-NBIs injected from lower outboard are for off-axis heating. N-NBI is tangentially injected almost on-axis to co-direction to the plasma current. Combination of these NBI systems enables us to realize various heating/current drive conditions, flexibly.

JT-60U is also equipped with the LHRF system at 2GHz. The antenna having the multi-junction structure [19] locates above the equatorial plane. Power of LH waves can be controlled continuously up to 1.5 MW at every 10 ms, which gives advantage in controlling LHCD current in real-time. The parallel refractive index $N_\parallel$ of the primary component of the LH wave spectrum ranges 1.4-2.1, depending on the phase difference of the LH waves from two adjacent antenna modules. In order to obtain stable coupling of the LH waves, the gap between the plasma and the antenna front is controlled fixed during LHCD. The gap width is optimized with respect to better coupling and less heat load to the antenna from bombardment. Carbon grill [20] installed in front of the antenna was removed in this campaign.

3. Control of current profile in a high-\(\beta\) plasma using the off-axis LHCD

Steady attainable \(\beta\) in JT-60U is usually limited by a neo-classical tearing mode (NTM), when rational surfaces having $q=1.5$ or 2 exist. The NTM can be stabilized or avoided when the minimum of safety factor ($q_{min}$) is raised above the corresponding values. In positive-shear plasmas, increase in off-axis driven current decreases on-axis current, leading to rise in $q_{min}$. Thus, we expect to stabilize the NTM, using the off-axis current driver. While the NBCD system in JT-60U does not have continuous controllability of injection power, the LHCD system does. The LHCD is also a strong off-axis current driver [21], having large CD efficiency. Thus, we have constructed the real-time control system of $q_{min}$ using the off-axis LHCD. The safety factor profile is evaluated in real-time [1], at 9 spatial points of MSE diagnostic. In every time slices, $q_{min}$ is calculated as the quadratic minimum of 3 measurement points having smallest $q$. The system controls $q_{min}$ to a given reference value ($q_{min,ref}$) through the injection power of the LH waves ($P_{LH}$), according to the following relation; $dP_{LH}/dt = - \alpha (q_{min} - q_{min,ref})$. The proportional gain $\alpha$ (positive value) determines response of the system. Parallel refractive index ($N_\parallel$) that affect LHCD location was fixed in this $q_{min}$ control.

The real-time control of $q_{min}$ has been successfully demonstrated in a high-$\beta_p$ ELMy H-mode plasma ($I_p=0.8$ MA, $B_t=2.5$ T, $q_{95}=5.9$) shown in Fig. 2. During constant NB heating phase at 11 MW, LH waves was injected at $t=7.5$ s, and the real-time control of $q_{min}$ started from $t=8$ s. The initial LH power before the control ($t=7.5$-8 s) was preprogrammed at 0.55MW. LH waves are injected at fixed $\Delta \phi=30$° (primary

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**FIG. 2.** Waveforms of the discharge for real-time $q_{min}$ control. (a) plasma current (red) and loop voltage (blue), (b) neutral beam power (red) and normalized $\beta$ ($\beta_N$, blue), (c) command LH power (blue) and injection power, (d) $q_{min}$ calculated in real-time (red) and reference of $q_{min}$ (blue), (e) a line averaged electron density, (f) electron temperatures at $\rho = 0.17$ (red), 0.37 (blue), 0.63 (green).
The reference value of $q_{\text{min}}$ is set to 1.3 during $t=8-10$ s. During $t=10-13$ s, the reference of $q_{\text{min}}$ is proportionally increased from 1.3 to 1.7, and the $q_{\text{min,ref}}$ was kept constant after $t=13$ s. After the start of $q_{\text{min}}$ control, $q_{\text{min}}$ was about 1.1-1.2 and slightly lower than the $q_{\text{min,ref}}=1.3$. Thus, the $q_{\text{min}}$ controller gradually increases the LH power after $t=8$ s. Since the proportional gain $\alpha$ was 2 MWs$^{-1}$ in this discharge, difference of $q_{\text{min}}$ and $q_{\text{min,ref}}$ of 0.1 gives increasing rate in the LH power of 0.2 MWs$^{-1}$. The minimum of $q$ profile near the plasma center started increasing at $t=9.5-10$ s. Since the increasing rate of $q_{\text{min}}$ during $t=10-13$ s was about the same as that of $q_{\text{min,ref}}$, the $q_{\text{min}}$ controller stopped increasing the LHCD power. At the LH power of about 1 MW, $q_{\text{min}}$ increased from 1.3 to 1.7, taking 3 seconds. The LH power is properly controlled so as not for the $q_{\text{min}}$ to overshoot its reference. During $t=13-15$ s, $q_{\text{min}}$ was controlled to 1.7 until the start of the notching of the LH power at $t=15.3$ s. The notching was caused by interlock of the LHRF system at arc-detection in front of the antenna. Figure 3 shows the safety factor profiles before and during the $q_{\text{min}}$ control. The safety factor inside $\rho=0.3$ was clearly raised by the LHCD through the $q_{\text{min}}$ control. During the notching of LH power, effective injection power was decreased, and the LH driven current was not enough to sustain $q_{\text{min}}=1.7$ so that $q_{\text{min}}$ gradually decreased down to 1.3. In this discharge, increase in $\beta_N$ (from 1.3 to 1.6) was observed after $t=12.5$ s, when $q_{\text{min}}$ was raised. Along with this increase in $\beta_N$, a line averaged electron density starts increasing and electron temperature also increased in the center of the plasma.

Although $q_{\text{min}}$ does not significantly change during $t=8-10$ s, current profile (or q profile) inside $\rho=0.5$ is changing due to the application of LHCD. Figure 4 shows the contour plot of the current density profile $j(\rho, t)$. During $t=7.5-10$ s, current density at $\rho=0.2$ is decreasing so that q is increasing. In Fig. 4, we can also see that the current density increases at $\rho=0.3-0.5$, after application of the LHCD and the $q_{\text{min}}$ control. Change in current density outside $\rho=0.6$ is small. This increase at $\rho=0.3-0.5$ is a result of spatially localized LHCD at this location. Spatial diffusion of inductive electric field (so called, back electromagnetic field) brings decrease in current density inside $\rho=0.2$, and increase in $q_{\text{min}}$. Increase in the current density at $t=13-15$ s at $\rho=0.2$ is caused by increase in the bootstrap current and decrease in the electric resistivity due to the increase in the central electron temperature as seen in Fig. 2 (f). The increase in the central electron temperature could be attributed to the q profile change [10] through the $q_{\text{min}}$ control. Thus, the current profile and temperature (or pressure) profile are interacting each other in a complex manner. In such a plasma, the real-time control of $q_{\text{min}}$ was demonstrated.
Figure 5 shows waveforms of the discharge where an MHD instability was clearly suppressed through the $q_{\text{min}}$ control. In order to produce a high-$\beta_p$ mode plasma, 14 MW of NBs were injected into a plasma having $I_p=0.8$ MA, $B_t=2.4$ T ($q_{95}=5.4$) during the flattop phase of $I_p$. When the diamagnetic stored energy $W_{\text{dia}}$ reached 1.55 MJ ($\beta_N=1.7$, $\beta_p=1.5$), the $m/n=2/1$ NTM appeared, leading to decrease in $W_{\text{dia}}$ by 22%. The electron density fluctuation profile measured by beam emission spectroscopy (BES) using MSE optics [22] shows fluctuation is spatially localized around the $q=2$ surface identified by the conventional MSE diagnostic. The phase of the density fluctuation between two channels in opposite side of $q=2$ surface are inverted, suggesting magnetic island structure [22]. The LH waves were injected after $t=7.5$ s. The $q_{\text{min}}$ control by $P_{\text{LH}}$ starts at $t=8$ s, at fixed $\Delta \phi=0^\circ$ (primary $N_e/\sim1.65$). We set $q_{\text{min,ref}}=1.7$ to eliminate $q=1.5$ rational surface in the plasma. The $q_{\text{min}}$ control started, $P_{\text{LH}}$ increased to raise $q_{\text{min}}$. The $q_{\text{min}}$ reached to 1.7 at $t=10$ s, and the LH power decreased by the control. The $q_{\text{min}}$ overshot the $q_{\text{min,ref}}$, and reached to 2 at $t=11$ s. The overshoot in $q_{\text{min}}$ might be caused by insufficient adjustment of the proportional gain $\alpha=0.3$ MW s$^{-1}$. At this time, the magnetic and density fluctuations at 1.6 kHz was suppressed, and $W_{\text{dia}}$ started increasing back to the initial value. Due to the reduction of LH power from $t=10$ s, $q_{\text{min}}$ decreased down to $q_{\text{min,ref}}=1.7$ at $t=12$ s.

4. Measurement of off-axis NB driven current profile

The off-axis NBCD profile was measured in an ELMy H-mode plasma having $I_p=1.2$ MA, $B_t=3.8$ T, and $q_{95}=5.4$. There was no MHD instability including sawtooth, except ELMs. A tangentially line averaged electron density is $n_e=3.3 \times 10^{19}$ m$^{-3}$. Figure 6 shows the waveforms of the discharge. During the flattop phase of the plasma current, 4 units of NBs (total 9MW) are injected. Three units of NBs are diagnostic beams; two for current profile measurement using MSE diagnostic and one for ion temperature measurement using CXRS diagnostic. Momentum input is almost balanced in the diagnostic beams. Another one unit is allocated for the off-axis NBCD or compensation of heating power using off-axis perpendicular injection P-NB; see Fig. 6 (b). Thus, the electron density and the diamagnetic stored energy (or the averaged pressure) are kept almost constant during most of the NB injection phase (Fig. 6 (c) and (d)). Figure 7 shows the poloidal cross section of the plasma, optimized for tangential NB #10 to pass sufficiently off-axis and for diagnostic beam to pass on-axis. About 2MW of the co-off-axis NB is injected during $t=7-12$ s. Plasma current is fully penetrated at the beginning of the start of the off-axis NBCD. At the electron density in this discharge ($n_e=3.3 \times 10^{19}$ m$^{-3}$), absorption of NB is sufficiently large, and slowing-down time of beam ions (about 0.2 s) is much less than the off-axis co NBCD duration (5 s).

Figure 8 (b) shows a contour plot of increment in total current $\delta I$ enclosed between adjacent MSE measurement points. This analysis technique [14] is good at showing small spatiotemporal change in current profile, when plasma configuration and quantities relating to equilibrium (such as stored energy shown in Fig. 6 (d)) are fixed in time. The reference of the
increment is the current profile at $t=8.9$ s (0.1 s before the start of the NBCD), as shown in Fig. 8 (a). A clear spatially localized increase in current has been observed at $\rho=0.69-0.79$ by the application of the off-axis NBCD ($t=9-14$ s). Thus, the off-axis NBCD contributes to the change in current profile. Due to the off-axis NBCD, current near the plasma center decreased, suggesting controllability of the central current or the central $q$ through the off-axis NBCD. The change in current profile gradually starts after the application of the off-axis NBCD. In about 2.5 s from the start of the NBCD, the local change in current profile has reached a steady-state, where the resistive diffusion time [23] is 2.3 s.

Loop-voltage profile analysis technique [24] using the MSE diagnostic shows that the toroidal electric field profile $E_\phi(\rho)$ is almost spatially uniform (within $\pm 7 \%$ variation in $\rho=0-1$) during $t=11-13$ s. Subtracting the Ohmic and bootstrap current profiles ($\alpha_x(\rho)E_\phi(\rho), j_{BSx}(\rho)$) from the total current profile $j_{totx}(\rho)$ gives the beam driven current profile $j_{BDx}(\rho)$. Here, we adopt the neo-classical conductivity $\eta_x$. The bootstrap current profile is calculated by the ACCOME code [25]. Slight on-axis beam driven current that is not fully canceled by the balanced injection of the diagnostic beams is also subtracted to clearly show the off-axis NBCD profile. Red bars in Fig. 9 (a) shows profiles of the beam driven current $j_{BDx}$ within a shell having thickness of $d\rho=0.02$, where $dS$ is the area of poloidal cross-section of the shell. The location of $j_{BDx}$ at $\rho=0.7-0.8$ in Fig. 9 (a) is consistent with the location of current increase in Fig. 8 (b). Since MSE directly measures pitch angle of the magnetic field line that is equivalent to “current” in a magnetic surface, comparison of “current” gives less ambiguity than comparison of “current density”. Figure 9 (c) shows chord-integrated neutron production rates $S_n$ [16] during and after the NBCD, as a function of the tangential minor radius $\rho_{\text{min}}$. The neutron production rate profile is normalized by that before off-axis NBCD application. The normalization is done to eliminate the effect of 3 units of the diagnostic NBs. The sight lines are shown in Fig. 7. Since estimated thermal ion contribution (th-th) to neutron yield is about 10 %, the rate can be a measure of the number of beam ions. Considering that the Fig. 9 (c) is plotted as a function of $\rho_{\text{min}}$, increase in the neutron production rate, and hence, the beam particle population during the application of the off-axis NBCD is localized within $\rho=0.61-0.78$. Again, the result is consistent with Fig. 8 (b) and Fig. 9 (a).

Here, we compare the experimental results with the theoretical calculations. Blue bars in Fig. 9 (a) shows $j_{BDx}$ calculated by the ACCOME code. Comparing with the experimental

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**FIG. 6.** Waveforms of discharge for off-axis NBCD profile measurement; (a) plasma current (red) and loop voltage (blue), (b) total NB power (red), off-axis co-NB power (blue), and perpendicular NB power that compensate total NB power during stop of off-axis co NBCD (green), (c) a line averaged electron density, (d) diamagnetic stored energy.

**FIG. 7.** Poloidal cross-section of the plasma and projection of trajectories of P-NB and N-NB. In order for NB#10 to pass enough off-axis, configuration was optimized. Sight lines of neutron emission profile measurement are drawn.
profiles, the location is inward shifted. The reason of discrepancy of the location is not understood yet. Sum of the currents within the shells in Fig. 9 (a) gives the total driven current $I_{BD}$. The measured off-axis beam driven current $I_{BD}$ was $0.11 \pm 0.04$ MA, while calculated one was 0.09 MA. Thus, the total amount of the beam driven current is consistent between the measurement and the ACCOME calculation.

Current drive efficiency of the off-axis NBCD was $\eta_{CD}=0.57\pm0.22 \times 10^{19}$ AW$^{-1}$m$^{-2}$ at local electron temperature of 1.8-2.2 keV at $\rho=0.7$-0.8, and effective charge number of $Z_{eff}=2.8$.

The similar analyses have been applied to another discharge having smaller $I_p$ (0.8MA). The experimental $j_{BDdS}$ is indicated by red bars in Fig. 9 (b). Spatially localized beam driven current is also observed off-axis. Figure 9 (d) shows corresponding neutron production rate profiles, showing broader profile than that at $I_p=1.2$ MA (Fig. 9 (c)). The peak location of $S_n$ suggests beam particles exist at $\rho=0.65$-0.81. Again, the location is consistent with experimental $j_{BDdS}$ profile. The CD location by the ACCOME calculation (blue bars in Fig. 9 (b)) is inward shifted than the measurement, as is seen in

FIG. 8. (a) Total current density profiles evaluated by equilibrium reconstruction using pitch angles measured by MSE diagnostic. Dotted curve shows $j(\rho)$ at $t=8.9$ s (0.1 s before the start of the off-axis NBCD). Solid curve is $j(\rho)$ at $t=12.5$ s (3.5 s after the start of the off-axis NBCD). (b) Temporal evolution of increment of current (kA unit) from current profile at $t=8.9$ s (Fig. 8 (a)) in case of the co-off-axis NBCD during $t=9$-14 s. Increase in current is indicated by light colors, while decrease by dark ones. Spatially localized increase in current was clearly observed at $\rho=0.7$-0.8.

FIG. 9. (a) and (b) Profiles of beam driven current $j_{BDdS}$ within a shell having thickness of $d\rho=0.02$ in the experiment (red) and in the ACCOME calculation (blue) at (a) $I_p=1.2$ MA and (b)$I_p=0.8$ MA. The measured NBCD profile is spatially localized at off-axis. CD location in Fig. 9 (a) is consistent with Fig. 8 (b). (c) and (d) Chord-integrated neutron production rate profile $S_n(\rho_{min},t)$ during NBCD, and 0.3 s after NBCD for (c) $I_p=1.2$ MA and (d) $I_p=0.8$ MA. Horizontal axis $\rho_{min}$ shows minimum of minor radius along diagnostic sight line.
Ip=1.2MA case. Total amount of the beam driven currents in the experiment and the calculation were 0.13 ± 0.03 MA and 0.10 MA, respectively. Thus, the similar result is obtained in the low Ip discharge. Although the ACCOME calculation does not take shifted guiding-center-orbit into account, this cannot explain the inward shift of CD location in calculation than the experiment, since the guiding center of co-passing ions born at the lower-field-side of torus (as in this calculation) passes more inward at the higher-field side. Thus, CD location in calculation moves more inward, when the guiding-center-orbit is taken into account. The reason should be studied in future.

5. Summary

We have developed the real-time control system of qmin using the off-axis current drive. Injection power of the lower-hybrid waves, and hence, its off-axis driven current controls qmin. In a high-\(\beta\) plasma, the real-time control of qmin is demonstrated, where qmin follows the temporally changing reference qmin,ref from 1.3 to 1.7. Applying the control to another discharge having m/n=2/1 NTM (\(\beta_N=1.7, \beta_p=1.5\)), qmin was raised above 2 through the control, and the NTM was suppressed. The stored energy increased by 16 % with the NTM suppressed. We have measured the current density profile for the off-axis neutral beam current drive (NBCD), using motional Stark effect (MSE) diagnostic. A spatially localized NBCD profile was clearly observed at \(\rho=0.6-0.8\). The location was also confirmed by the multi-chordal neutron emission profile measurement. The total amount of the driven current was consistent with the theoretical calculation using the ACCOME code. The discrepancy is that the CD location in the calculation was inward shifted than the measurement.

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