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# The Universal Constant Connecting the Theta and F Values in Reversed Field Pinch Configurations on ATRAS-RFP Plasma

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The values of pinch parameter, $\Theta\left(\equiv B_\theta(a)/\langle B_t\rangle\right)$, and reversal parameter, $F\left(\equiv B_t(a)/\langle B_t\rangle\right)$ characterizing the field configuration of reversed field pinch (RFP) plasma are changed during the RFP discharge by the control of the plasma current and the toroidal field on the plasma surface. But these values are connected by an equation of $\Theta/(1-F)=const.$, and the value is round the 1.5 in ATRAS-RFP plasma. This is also described by other expressions, as follows,

$$\frac{\Theta}{1-F}=\frac{\mu_0 a I_p}{2\Phi_{I\theta}}=\frac{B_\theta(a)}{\langle B_{tI\theta}\rangle}.$$

Where, $\Phi_{I\theta}$ is toroidal flux produced by the poloidal current flowing in the plasma column only, and $\langle B_{tI\theta}\rangle$ is its averaged magnetic field. That are,

$$\Phi_{I\theta}=2\pi\int_0^a\{B_t(r)-B_t(a)\}rdr,\quad \langle B_{tI\theta}\rangle=\Phi_{I\theta}/\pi a^2,$$

where $a$ is radius of the plasma column. This is saying that this quantity does not depend on the experimental apparatus and is characteristic constant for RFP plasma. The values of $\Theta/(1-F)$ at the peak of plasma current for 470 RFP discharges having various $\Theta$ and F values on our ATRAS RFP device are shown in Fig. 1 with the values of $\Theta$ and F at the same time. This constancy is also hold from the start of the RFP configuration to the disruption in ordinary discharge. To examine what condition breaks the constancy of $\Theta/(1-F)$, we added high frequency (3.8 kHz) toroidal electric field to ordinary RFP discharge at the peak plasma current. The typical results for the values of $\Theta/(1-F)$, $\Theta$ and $F$ are shown in Fig. 2. We can see a tear of constancy of $\Theta/(1-F)$ in the decreasing phase of $\Theta$ value, when large amplitude oscillating toroidal electric field is applied. We discuss here the characteristic of RFP plasma for the constancy of $\Theta/(1-F)$ with the field configuration obtained by using of inner magnetic probes. The radial distributions of the toroidal magnetic field produced by inner poloidal

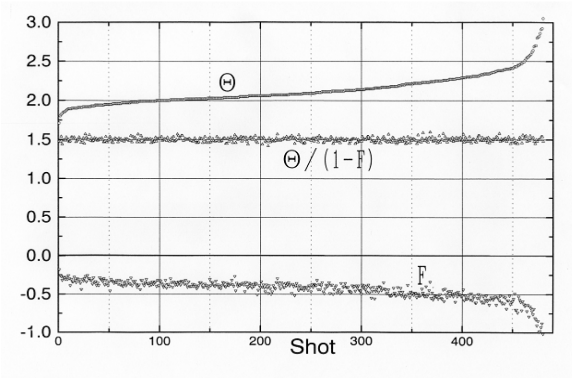


Fig. 1 The values of $\Theta/(1-F)$ at the peak plasma current for normal RFP discharges having various $\Theta$ values.

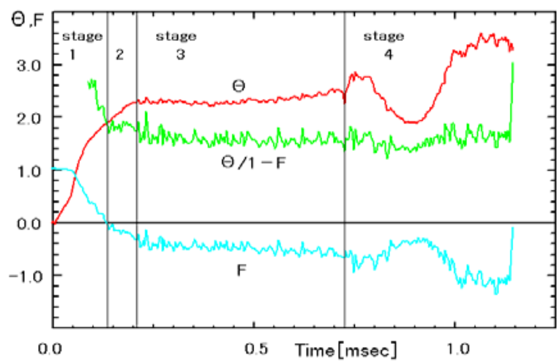


Fig. 2 The time history of $\Theta$, $F$ and $\Theta/(1-F)$ values for a RFP discharge with additional oscillating E field.

plasma current are shown dividing in 4 stages. These profiles are normalized to one at the magnetic axis to see the transition of it. The first stage is the duration before the field reversal. The profile is spreading out in the central region and has a minimum in the outer region of the plasma column. The minimum point spread out decreasing the value toward the plasma surface with time. As soon as it reaches the plasma surface, field reversal begin. These progresses are shown in Fig.3(a). The value of $\Theta/(1-F)$ decrease remarkably as seen in Fig.2. The second stage is the duration of that the RFP configuration is constructed but $\Theta$ value is increasing and F value decreasing remarkably. However, the value of $\Theta/(1-F)$ slightly decreasing reaches to the final constant value. In this phase, the profile contract toward the magnetic axis in the all region of the plasma column with the reversal surface and minimum point disappear (Fig.3(b)). The third stage is the almost stable phase of $\Theta$ and F values. The toroidal field profiles which is made by the poloidal current flowing in the plasma column is fixed almost in this duration (Fig.3(c)). In the forth stage, oscillating toroidal electric field having the same sign in the first quarter period to the electric field sustaining the RFP configuration is applied by the additional Ohmic circuit. The plasma current is increased with the toroidal magnetic flux which is produced paramagnetically and has the peak delaying about $50\mu s$ from the current peak. In the decreasing phase of toroidal flux positive poloidal electric field is induced. This assists to drive the positive poloidal current in the outside of the reversal surface and make shallow the field reversal by the current induced in the metal liner. But, because the decreasing ratio of the $\Theta$ value is lager than that of $(1-F)$, the value of $\Theta/1-F$ becomes smaller than the universal value as seen in Fig.2. The radial profile of the toroidal magnetic field becomes large in the outer region of plasma column by the assistant of induced positive electric field as seen in Fig.3(d).

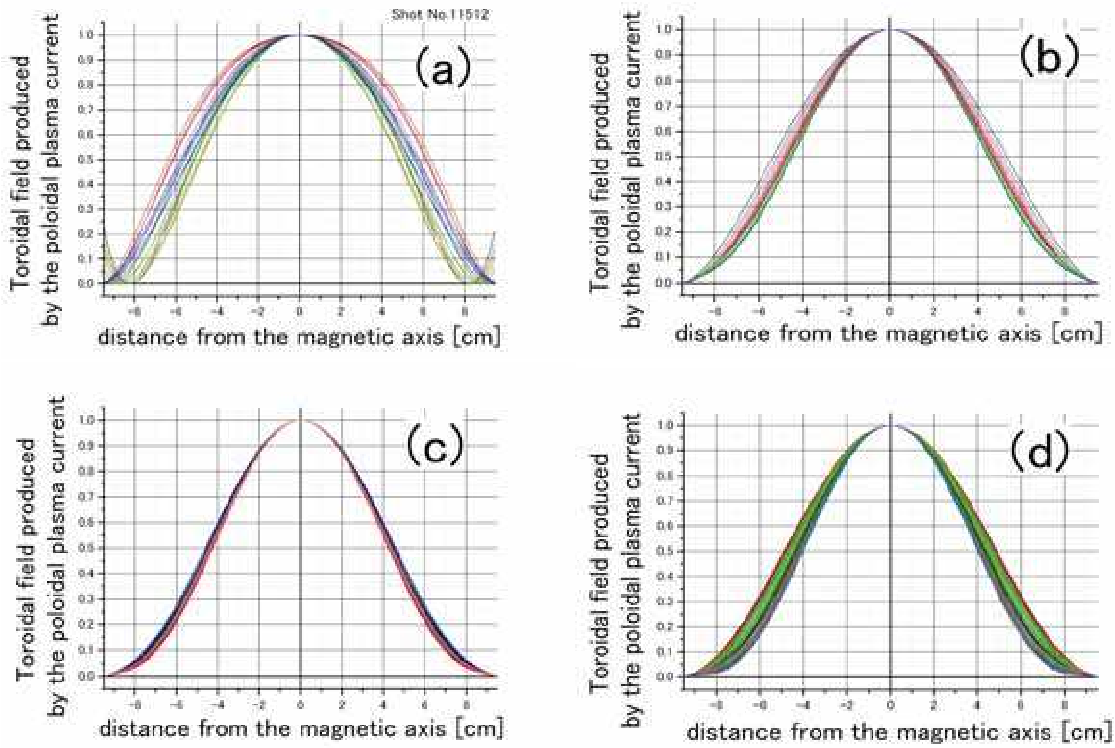


Fig.3. The time history of the radial distribution of the toroidal field produced by the poloidal current flowing in plasma in each stage; (a) before the RFP configuration, (b) RFP has constructed but F and $\Theta$ are changing, (c) F and $\Theta$ are constant but plasma current is increasing, (d) the large amplitude high frequency toroidal electric field is applied.

<u>Discussions</u> Toroidal magnetic field produced by the poloidal plasma current decrease monotonically from the magnetic axis to the plasma surface. So the direction of poloidal current flowing in the plasma has positive sign all over plasma column. This is essential to maintain the RFP configuration which is driven by external toroidal electric field. If the poloidal current reverse in the outside of the reversal surface, toroidal field decrease from the plasma surface to the reversal surface and the reversal surface moves toward the magnetic axis broadening reversal region of the toroidal field. Finally it reaches the axis and the RFP configuration crash. The plasma currents driven by the Ohm’s law are

described as $\vec{E} = \vec{\eta} \cdot \vec{j}$. Where, we assumed that the plasma has different resistance parallel and perpendicular to the magnetic field. We denote these to $\eta_{//}$ and $\eta_{\perp}$ respectively. And the ratio is denoted as $D \equiv \eta_{\perp} / \eta_{//}$. Then poloidal and toroidal plasma currents are described as follows,

$$j_p = \frac{B_t B_p}{\eta_{//} B^2}\left(1 - \frac{1}{D}\right)E_t + \frac{1}{\eta_{//} B^2}\left(B_p{}^2 + \frac{B_t{}^2}{D}\right)E_p,$$

$$j_t = \frac{1}{\eta_{//} B^2}\left(B_t{}^2 + \frac{B_p{}^2}{D}\right)E_t + \frac{B_p B_t}{\eta_{//} B^2}\left(1 - \frac{1}{D}\right)E_p.$$

Where, $E_t$ is the toroidal electric field externally driven by OH circuit and $E_p$ is the poloidal field induced by the fluctuation of the toroidal flux in the magnetic surface. The first term of the poloidal current is positive in the reversal surface and negative in the outer region of it, because D is larger than one in usual plasma and toroidal field change the sign in the outside of the reversal surface. The second term changes the sign according to the increase or decrease of the toroidal flux in the magnetic surface. In the rising phase of the plasma current poloidal current is negative in the outer region of the reversal surface because of $E_p < 0$ and RFP configuration will crash at the moment. But the experimental results show that the poloidal currents have positive sign all over the plasma column as seen in Fig.3(b,c,d) and the RFP configuration is maintained during the existence of the appropriate toroidal electric field with the high frequency large amplitude oscillating toroidal magnetic field. This result is explained by the existing of the some mechanism making D smaller than one or dynamo effect. In the decreasing phase of toroidal flux, the flux induces the positive poloidal electric field which assists the sustainment of the RFP configuration decreasing the fluctuation of the magnetic field as like as the PPCD.

Conclusions The tear of the universality of the constancy of $\Theta/(1-F)$ is small for the application of the large amplitude high frequency oscillating toroidal electric field even then the values of F and $\Theta$ are violently varied by it. And, the toroidal field configuration produced from the poloidal current flowing in the plasma column does not change the shape excepting the slightly increase in the outer region of the column. These results suggest that the application of the oscillating toroidal electric field can induce the stabilizing effect to the RFP plasma even by the resistive wall and enable to keep it in stable statically.