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Effects of Periodic Helical Deformation Occurrences on the Flux Generation (Dynamo) in RFP

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Abstract

Effects of periodic helical deformations on the dynamo mechanism in RFP are examined using a simple electric circuit model. Modeling the plasma to toroidal and poloidal current channels, we use the method which switches mutual inductance matrices discontinuously on the condition conserving magnetic flux to simulate periodic onset and extinction of helical deformations.

And even if helical deformations occur periodically, phenomena of continuous energy transports from a poloidal external power source to a toroidal circuit and toroidal flux sustainment with appropriate Θ value are shown to be demonstrated using the proposed circuit model.

Keywords:
RFP, helical deformation, dymano, electric circuit model

1. Introduction

The mechanism for self-generation of magnetic flux (dynamo effect) has been studied experimentally and theoretically as for sustainment and improvement of RFP plasma confinement. Most studies on this effect, such as magnetic reconnection, have concentrated those attentions on one time deformation behavior of RFP plasma for a toroidal flux generation. But many experimental observations, such as ramped current discharge at ZT-40M [1] and spontaneous generation of toroidal flux at toroidal Z-pinch [2], suggest the strong coupling between toroidal and poloidal plasma currents and the continuous energy transport from poloidal to toroidal circuit.

Therefore, using simple electric circuit model, we investigate effects of the periodic occurrence of helical deformations on the generation and sustainment of a magnetic flux. In Sec. 2, electric circuit model is derived, in Sec. 3 analyzed results and comparison those with experimental data are described. Discussions and conclusions are made in Sec. 4.

2. Electric Circuit Model for Helical Deformed RFP Plasma

The electric circuit model is useful for analysis of an energy transport between toroidal and poloidal circuit including external power sources and comparisons of waveforms with experimental data.

Used toroidal RFP plasma model is shown in Fig. 1, where Φ_t and Φ_p are magnetic flux of toroidal and poloidal direction, respectively. Figure 2 shows parameters specifying helical deformed plasma where r_p is a minor radius of plasma, r_h is a displacement of plasma column from the center of discharge chamber $(r, z) = (R_0, 0)$, and θ_h is an angle from r-axis and is expressed using toroidal helical mode number n as $\theta_h = n\theta$.

In this model, we consider two current components of toroidal and poloidal directions, where in an symmetric case, those current are independent, and in helical deformed case those are coupled through mutual inductance. In table 1, we show approximate equations of self- and mutual inductances.

The time scale from start to its final steady state of helical deformation must be much smaller than that of resistive diffusions. So, motions of helical deformations are treated as if they occur instantaneously, conserving magnetic flux. To simulate these conditions, we adopted the electric circuit in Fig. 3, where in Fig. 3(b) deformation process from symmetric to helical plasma is treated as changing values of circuit parameters, discontinuously. Moreover, for simplicity, poloidal one turn voltage is set to zero, although it is applied to sustain negative toroidal field, and toroidal current is treated as current source I_t.

3. Analysis of Periodic Deformed Plasma

In the following analysis, values of time, electric current, magnetic flux, inductances and resistances are normalized by those specific values.

Figure 4 shows time histories of toroidal magnetic flux Φ_t and poloidal current I_p on condition of steady and periodic occurrence of helical deformations, where the duration of symmetric τ_1 and helical deformed plasma τ_2 are 0.1 and 0.01, and L_{p1}/R_{p1} = 1, L_{p2}/R_{p2} = 0.12. In periods of Φ_t rising and I_p dropping, plasma is in a helical form. From this figure, toroidal flux is shown to be generated and conserved in case of periodic helical occurrences as well as in case that plasma remains in a helical form. And this phenomena is interpreted as follow;

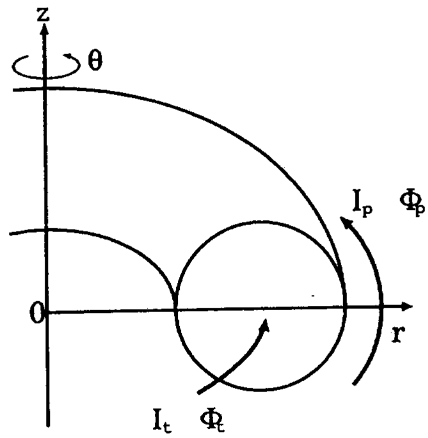


Fig. 1 Definition of toroidal and poloidal current I_t, I_p and flux Φ_t, Φ_p in the cylindrical coordinate.

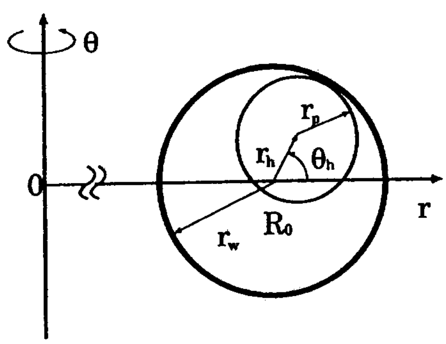
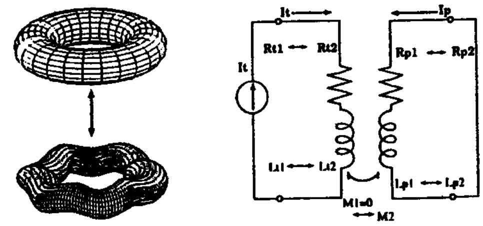


Fig. 2 Definition of a helical deformed plasma. (Figure is shown in case of r_h/r_w = 0.5.)

Table 1 Approximate forms of self and mutual inductance of plasma.

L_{t1}	L_{p1}	M_1
$\mu_0 R_0(\ln(8R_0/r_p) - 2)$	$\mu_0(R_0 - \sqrt{R_0^2 - r_p^2})$	0
L_{t2}	L_{p2}	M_2
$L_{t1} + \mu_0 n^2 r_h^2/2R_0$	$L_{p1}/\sqrt{1 + (nr_h/R_0)^2}$	$\mu_0 r_h^2 n/2R_0$



(a) Symmetric and helical deformed plasmas

(b) Swithing circuit model

Fig. 3 Forms of a symmetric and a helical deformed plasma (a) and the electric circuit model used periodic deformed plasma analysis (b).

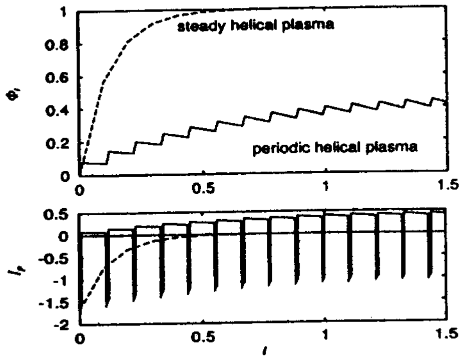


Fig. 4 Typical waveforms of a toroidal flux and poloidal current in case of steady and periodic helical deformed plasma.

i) at first, toroidal flux is generated by a helical deformed toroidal current ($M_2 I_t$).

ii) at a time changing from helical to symmetric plasma, poloidal current (I_p) is driven to conserve Φ_t, and due to resistive dissipation, Φ_t decreases gradually.

iii) again at a time changing to helical deformed plasma, to conserve Φ_t in the presence of $M_2 I_t$, I_p droppeds to negative value instantaneously. And due to resistive dissipation of $|I_p|$, Φ_t increases further.

And the steady state value of toroidal flux $\overline{\Phi}_t$ is deduced as follow

$$\overline{\Phi}_t = \left(\frac{1-\alpha_2}{1-\alpha_1\alpha_2} \right) M_2 I_t$$

where $\alpha_1 \equiv \exp(-R_{p1}\tau_1/L_{p1})$, $\alpha_2 \equiv \exp(-R_{p2}\tau_2/L_{p2})$ and $M_2 I_t$ is a flux that may be sustained in case that plasma deforms helically in steady state. Figure 5 shows dependences of $\overline{\Phi}_t/M_2 I_t$ on α_1 and α_2. And on conditions of $\alpha_1 \sim 1$ or $\alpha_2 \sim 0$, larger toroidal flux is sustained.

From above analysis, pinch parameter $\Theta = \langle B_{pw} \rangle / \langle B_t \rangle$ may be calculated as

$$\Theta = \frac{\mu_0 r_w}{2} \frac{I_t}{\Phi_t} = \frac{(1-\alpha_1\alpha_2)}{(1-\alpha_2)} \cdot \frac{\mu_0 r_w}{2M_2}$$

$$\sim \frac{(1-\alpha_1\alpha_2)}{(1-\alpha_2)} \cdot \frac{1}{k r_w} \left(\frac{r_w}{r_h} \right)^2 ,$$

where $k = n/R_0$ is a toroidal wavenumber of a helical deformation, r_w is a minor radius of the shell. Using $r_h/r_w = 0.5$ typically, because the deformation should be an internal mode, in table 2 we show evaluated Θ values of devices HBTX-1 [3], HBTX1B [4], TPE-1RM15 [5], where $(1-\alpha_1\alpha_2)/(1-\alpha_2) = 1$. And derived values of Θ from our circuit model are shown to agree approximately with experimentally measured values.

4. Discussions and Conclusions

The direction of a helical deformation of RFP plasma has been recognized experimentally [6] to the one increasing the toroidal magnetic field at plasma center. And the condition for the growth of helical deformation is also estimated approximately by the electric circuit model. Because of using current source I_t or discontinuity of a poloidal flux, the system energy relating to work done externally is given as

$$W^* \equiv \frac{1}{2}(\Phi_p I_t + \Phi_t I_p) - \Phi_p I_t ,$$

and waveforms of Φ_t and W^* on the same conditions of Fig. 4 are shown in Fig. 6. Dis-continuous drops of W^* are interpreted to correspond to the free energy making grow helical deformations which is indeed identical to the kink instability.

In conclusion, modeling periodical helical deformations of RFP plasma in simplified electric circuit, continuous energy transport from a external poloidal circuit source to a toroidal circuit, generation/ sustainment of toroidal flux are shown to be demonstrated. And from Θ estimations, sustained toroidal flux agree with experimental values.

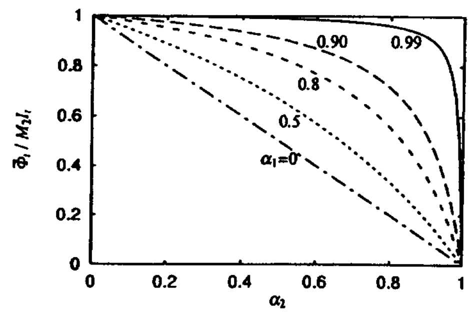


Fig. 5 A dependence of the coefficient $\overline{\Phi}_t/M_t I_t$ on α_1 and α_2.

Table 2 Comparison the proposed Θ value with experimental ones.

Device	HBTX-1[3]	HBTX1B[4]	TPE-1RM15[5]
$\Theta(kr_w)$	0.8 (4.5)	2.56 (1.6)	1.11 ~ 1.8 (2.2 ~ 3.6)

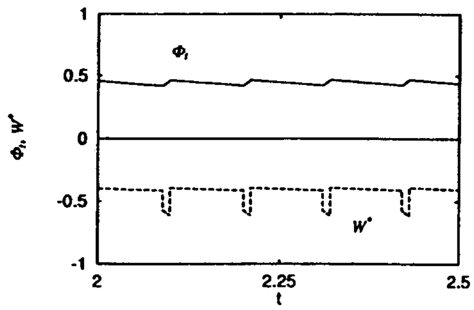


Fig. 6 Waveforms of a toroidal flux and the system energy W^* relating to the work done externally.

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