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TECHNOLOGY AND PHYSICS IMPLICATIONS OF OSCILLATING-FIELD CURRENT DRIVE IN REVERSED-FIELD PINCHES[†]

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ABSTRACT

The property of reversed-field pinches (RFPs) to relax to a near-minimum-energy state is the basis of oscillating-field current drive (OFCD), wherein plasma current is driven by modulating in quadrature the external toroidal and poloidal magnetic fields. Coupled plasma/circuit OFCD simulations of RFPs ranging from present experiments (ZT-P and ZT-40M) to the reactor (TITAN) indicate that the drive frequency and the amplitude of the plasma-current oscillations decrease and the "wall-plug" current-drive efficiency increases with decreased plasma resistance so that minimum frequencies (~ 25 Hz) and plasma-current amplitudes ($\sim 1.6\%$) and maximum efficiencies (~ 0.3 A/W) are attained in the reactor regime. Methods for minimizing the reactive powers and for optimizing the current-drive efficiency for OFCD in RFPs have been identified.

1. INTRODUCTION

The property of reversed-field pinches (RFPs) to relax to a near-minimum-energy state^{1,2} may be exploited to drive a steady-state plasma current.^{3,4} Relaxation processes related to turbulence and/or resistive instabilities can convert toroidal magnetic energy into poloidal magnetic energy and vice versa, while maintaining the near-minimum-energy RFP state that is characterized by large on-axis toroidal field (comparable to the edge-plasma poloidal field) which decreases to a low, reversed value outside the plasma. During oscillating-field current drive (OFCD), the toroidal and poloidal magnetic fields at the plasma surface are modulated in quadrature (i.e., $\pi/2$ phase shift). These nonlinear relaxation processes rectify the externally-driven modulations into a net steady-state plasma current and have been observed experimentally to produce a 5% increase in poloidal flux⁵ in relatively cold (resistive) plasma. Although inconclusive, these positive indications warrant an examination of OFCD to determine the reactor potential and to assess the physics and technology requirements. The full spectrum of RFPs ranging from present experiments (ZT-P⁶ and ZT-40M⁷) through devices under construction (ZTH⁷) to the reactor (TITAN⁸) are analyzed to estimate the requirements for developing OFCD technology.

II. PLASMA AND CIRCUIT MODELS^a

A. Plasma Model

The OFCD power flow is derived herein from energy balance⁴ rather than helicity balance.³ A power balance imposed at the plasma surface, a definition of the plasma internal magnetic energy, and a positive Faraday's Law ($V_\theta = d\phi/dt$) yield the following expression for the plasma toroidal loop voltage, V_ϕ :

$$V_\phi = I_\phi R_p + \left[L_p + \frac{\Theta}{2} \frac{dL_p}{d\Theta} \right] \dot{I}_\phi + \left[\frac{1-F}{\epsilon\Theta} - \frac{\epsilon\Theta^2}{2L_o} \frac{dL_p}{d\Theta} \right] V_\theta, \quad (1)$$

where $V_{\phi,\theta}$ are the toroidal and poloidal voltages applied to the plasma, R_p is the plasma resistance, L_p is the plasma internal inductance (not including vacuum toroidal flux), $F = B_\phi(r_p)/\langle B_\phi \rangle$ is the reversal parameter, $\Theta = B_\theta(r_p)/\langle B_\phi \rangle$ is the pinch parameter, $\langle B_\phi \rangle = \phi/\pi r_p^2$ is an average toroidal field within the plasma minor radius, r_p , and $L_o = \mu_0 r_p^2/2R_T$ is the vacuum toroidal inductance.

Oscillations of $V_{\phi,\theta}$ in proper phase can give a net time-averaged current, with the time-averaged toroidal voltage equal to zero (i.e., no net change in poloidal flux). The oscillation period, $T = f^{-1}$, must be longer than the plasma relaxation time to permit the rectification of the external-field modulations into a steady-state current but much shorter than the time for the resistive decay of the current (the plasma L/R time). One possible plasma relaxation process that increases the poloidal flux and is used for the basis of this discussion is a class of $m = 1$ MHD tearing modes⁹ which are described by the Kadomtsev reconnection model.^{9,10} The process that decreases the poloidal flux is a double reconnection¹¹ responsible for the "dynamo effect" in the RFP which maintains the large on-axis toroidal field. The characteristic growth time, τ_T , for these tearing instabilities is determined numerically^{9,11} to be $\tau_T \sim 100\tau_A$, where τ_A is an Alfvén transit time based on $B_\theta(r_p)$. Assuming a resistive MHD scaling (i.e., $\tau_T \propto S^{1/2}$), $\tau_T = (10\tau_A\tau_R)^{1/2}$ where $S = \tau_R/\tau_A$ is the Lundquist number, $\tau_R = \mu_0 r_p^2/\eta$ is the resistive plasma current decay time, and η is the plasma resistivity. The constraint on the period is $T > \tau_T$. The constraint $T < \tau_R$ is required to ensure sufficiently small

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amplitude field oscillations in order to maintain toroidal-field reversal (i.e., $F < 0$). The steady-state value of F determines the tolerable difference between T and τ_R . For all the devices considered here, $-0.2 \leq F \leq -0.1$, and $T \leq 10^2 \tau_R$ is needed to maintain reversal. Within these constraints a non-intrusive means to drive current using primarily the main confining coil system in a low-frequency, low-amplitude mode becomes possible for the RFP.

Solving Eq. (1) requires the Θ dependency of F , as well as the Θ dependency of the magnetic field, $\vec{B}$, and current density, $\vec{j}$, profiles, and hence, L_p and R_p . A circularized, one-dimensional MHD model described in Ref. 12 is used. The radial density, temperature, and $\mu \equiv \mu_0 \vec{j} \cdot \vec{B} / B^2$ profiles required as input to the MHD model are based on one-dimensional plasma simulations for FTF¹³ (fusion test facility) and TITAN⁶ (commercial reactor). Normalized density and temperature profiles of the form $[1 - (r/r_p)^3]$ and a flat normalized μ -profile of the form $[1 - (r/r_p)^8]$ are assumed for ZT-P and ZT-H. Given a poloidal beta, β_θ , and I_ϕ , the MHD model determines the corresponding value of F and Θ . An F - Θ curve is then generated by varying I_ϕ . The Θ dependency of L_p and R_p also is obtained by the appropriate integration of the MHD-model generated $\vec{B}$ and $\vec{j}$ profiles, respectively.

The algorithm for identifying steady-state solutions to Eq. (1) fixes the amplitude of a sinusoidal toroidal-flux function, $\delta\phi/\phi_0$, and iterates upon the amplitude of a sinusoidal toroidal-voltage function, $\delta V_\phi/V_{\phi 0}$, until the plasma current becomes periodic, i.e., $I_\phi(t) = I_\phi(t + T)$. The toroidal-flux and voltage functions are in phase to produce the maximum current drive. An initial guess for $\delta V_\phi/V_{\phi 0}$ is obtained from the constraint that the time-averaged helicity is constant which yields the following condition on the amplitudes of the toroidal-flux and voltage oscillations: $(\delta\phi/\phi_0)(\delta V_\phi/V_{\phi 0}) \simeq -2$. The plasma current is reset to the desired value at the beginning of each simulation period. The time scale also is adjusted to ensure that the mean current during a period equals the current at the beginning of the period.

B. Circuit Model

An assessment of OFCD efficiency requires the modeling of the circuit elements external to the plasma, as well as the plasma, in order to account for all power dissipation. The power flow is shown schematically in Fig. 1. The governing matrix circuit equation is written as follows

$$\vec{L} \frac{d\vec{I}}{dt} + \vec{R}\vec{I} = \vec{V}, \quad (2)$$

where $\vec{I}$ and $\vec{V}$ are column vectors representing the currents and voltages, respectively, $\vec{R}$ is a diagonal matrix of resistances, and $\vec{L}$ is the inductance matrix. The inductances in Eq. (2) are time independent, because $\vec{L}$ consists only

of the external circuit-element inductances and the plasma external inductance: the plasma internal inductance appears in Eq. (1). Circuit equations are derived for poloidal and toroidal current paths and are labeled θ and ϕ , respectively, according to the current direction.

A shell model is used to determine the inductances and the resistances used in the matrices. Standard wire and toroidal shell formulae¹⁴ for currents in the toroidal and poloidal direction, respectively, are used for the self-inductances. The mutual inductance between two elements is taken as the smaller self-inductance of the two elements. The resistance of a circuit element is determined by assuming the current flows in the smaller of either the current penetration skin depth or the annular thickness of the conducting shell.

The circuit elements simulated are the plasma, first wall or liner, the toroidal-field (TF) coils, the ohmic-heating (OH) coils, the blanket or shell, a primary equilibrium-field (EF) coil set, and an optional secondary equilibrium-field (trim) coil set (Fig. 1), which dissipate most of the power. The current vector $\vec{I}$ of Eq. (2), then, has components corresponding to each circuit element listed above. The plasma current in the toroidal-circuit is the I_ϕ solution to Eq. (1).

In solving Eqs. (1) and (2) simultaneously, the plasma resistance is taken as zero in Eq. (2), because it is already included in Eq. (1). The voltage vector of Eq. (2) contains the external voltages applied to the coils. The TF-coil voltage is determined by requiring the toroidal field at

Figure 1. Schematic diagram of the OFCD power flow

the plasma surface be produced by all the elements with continuous poloidal current paths. The OH-coil voltage is derived from the solution for I_ϕ from Eq. (1). If trim coils are used, the EF-coil voltage is maintained at a constant value corresponding to the mean equilibrium field. The voltage applied to the trim coil (the EF coil if trim coils are not used) is determined by requiring the trim coils to track the oscillating equilibrium-field requirement of the plasma.¹⁵ For passive elements like the first wall (liner) the applied voltage is zero. The applied toroidal plasma voltage in Eq. (2) is $-V_\phi$, because V_ϕ is a voltage drop as written in Eq. (1). The applied poloidal plasma voltage, however, is V_θ , because positive Faraday's law is used.

A need to model passive elements with resistive breaks or gaps arises for simulations of shells used in present-day experiments, which are designed with gaps to allow penetration of magnetic fields during the current-rise phase. Reactor first walls also are simulated with gaps to minimize power loss. The model derived here for circuit elements with gaps simulates each passive element as an inner and outer current path, as is shown in Fig. 2. The current is assumed to flow in the smaller of either half of the radial build of the passive element or a current penetration skin depth. The self-inductance of an element with gaps is the difference of the self-inductances of the inner and outer current-path elements. The mutual inductance between an element with gaps and a continuous element is the difference between the minimum of the self-inductances of the inner current-path element and the continuous element and the minimum of the self-inductances of the outer current-path element and the continuous element. The resistance of an element with gaps is the sum of the resistances of the inner and outer current-path elements.

The time-dependent current and voltage solutions to Eq. (1) are solved in conjunction with the $I_\phi(t)$ solution to Eq. (2). The electrical time constants of the external circuits are

Figure 2. The current paths envisioned for the passive circuit elements with resistive breaks orthogonal to the corresponding continuous current direction

sufficiently short so that periodic solutions to Eq. (1) and (2) are obtained simultaneously. The dissipated powers and peak reactive powers of the entire system are derived from the calculated current and voltage wave forms.

III. RESULTS

The algorithms described in Sec. II have been applied to the following air-core RFPs, which span the entire spectrum of RFPs: ZT-P,⁶ ZTH,⁷ FTF,¹³ and TITAN-II.⁸ The parameters that describe these devices are listed in Table I. The ZT-P device is a small prototype of ZTH which is presently under construction. The FTF device is a proposed "ignition" class RFP, which in a steady-state version could provide a neutron source for fusion technology testing.¹³ The reactor regime is represented by the steady-state, high neutron-wall loading (18 MW/m²) TITAN-II design.⁸ The TITAN-II design was selected in this study in order to preserve a common TF-coil design; namely, normal-conducting Cu-alloy TF coils positioned outside of the blanket/shell are used in all the devices considered. Table I also gives parameters for the ZT-40M device, which is an iron-core machine on which OFCD experiments have been conducted.⁵

The shell model is illustrated in Fig. 3 for ZT-P. A shell radius is determined by requiring the shell to approximate the physical location of the circuit element to be simulated. The thickness of a shell annulus is determined by requiring the shell to have the same resistance as the circuit element simulated. A comparison of ZT-P inductances calculated with this shell model and a high resolution, multi-filamentary

Figure 3. Cross-sectional view of ZT-P above the equatorial plane and the shell model below the equatorial plane

TABLE I. Device Parameters and OFCD Results for a Spectrum of RFPs

Parameter	ZT-P ⁶	ZT-40M ⁵	ZTH ⁷	FTF ¹³	TITAN II ⁴
Major toroidal radius, $R_T(m)$	0.45	1.14	2.40	1.8	3.90
Minor plasma radius, $r_p(m)$	0.062	0.18	0.381	0.3	0.6
Plasma temperature, $T_e(keV)$	0.3	0.15	2.0	9.0	9.5
Poloidal beta, β_θ	0.36	0.1	0.1	0.1	0.22
Effective charge, Z_{eff}	6.26	~ 3	3.93	1.69	1.69
Plasma toroidal loop voltage, $V_\phi(V)$	35(0.34) ^(a)	50.	7.0	2.3	1.6
Liner with or without gaps	without	without	without(with)	with	with
Plasma resistive time constant, $\tau_R(s)$	0.0026(0.26) ^(a)	0.002	1.73	20.3	109.
Oscillation period, $T = f^{-1}(ms)$	0.2	0.5	5.	16.7	40.
Tearing time constant, $\tau_T(ms)$	0.068(0.68) ^(a)	0.2	1.95	4.12	15.6
Lundquist number, $S(10^6)$	0.015(1.5) ^(a)	0.01	7.93	242.	487.
Average Plasma Current, $I_\phi(MA)$	0.08	0.06	2.	10.2	17.8
Drive Frequency, $f(Hz)$	5000.	2000.	200.	60.	25
Toroidal-flux swing, $\delta\phi/\phi_0$	0.035	0.05	0.035	0.035	0.035
Current swing, $\delta I_\phi/I_\phi(\%)$		7	6.4	2.4	1.6
Θ Variation		1.5-1.9	1.39-1.60	1.47-1.58	1.50-1.62
F Variation		-0.1 - -0.5	-0.03 - -0.36	-0.04 - -0.20	-0.03 - -0.17
Plasma dissipation, P_Ω	2.8	3.	14.0	23.3	28.6
Toroidal Circuit (MW):					
Plasma Poynting power, P_P^*			1,385.	2,826.8	3,960.0
First-wall dissipation, P_{FW}			30.7(0.0)	0.0	0.0
Blanket dissipation, P_B			0.6(0.4)	1.6	0.0
Poloidal Circuit (MW):					
Plasma Poynting power, P_P^*			41.2	114.9	247.3
First-wall dissipation, P_{FW}			6.2(0.0)	0.0	0.0
Blanket dissipation, P_B			2.8(1.6)	17.7	0.2
Terminal Reactive Power, $P_i^*(MVA)$					
OH coils			390.8(240.8)	3.3	102.0
TF coils			253.3(187.9)	944.3	1,413.2
EF coils			941.2(921.9)	67.2	$\sim 0^{(b)}$
Trim coils			--	817.6	147.2
Coil Dissipation, $P_i(MW)$					
OH coils			0.1(0.0)	0.0	0.2
TF coils			1.5(1.3)	10.6	35.7
EF coils			1.1(1.1)	54.6	$\sim 0^{(b)}$
Trim coils			--	26.3	2.5
Real (lost) Terminal Power, $P_i^T(MW)$					
OH coils			40.1(3.1)	0.1	1.2
TF coils			19.3(11.7)	44.2	62.5
EF coils			-2.6(3.4)	52.6	$\sim 0^{(b)}$
Trim coils			--	37.3	3.5
TF-coil dc power, $P_{TF}^{SS}(MW)$			1.0(1.0)	8.8	29.1
EF-coil dc power, $P_{EF}^{SS}(MW)$			1.1(1.1)	52.6	$\sim 0^{(b)}$
Power-supply dissipation, $P_{PS}(MW)$ ^(c)			15.9(13.5)	18.3	16.6
Current-drive power, $P_{CD}(MW)$		7	70.6(29.8)	91.0	54.6
Current-drive efficiency, $I_\phi/P_{CD}(A/W)$ ^(d)	0	0.0086	0.028(0.067)	0.11	0.33

(a) For the ZT-P parameters, OFCD is not possible. The values in parenthesis indicate the minimum change in loop voltage required to obtain unphysical steady-state solutions at 5 kHz.

(b) Superconducting EF coils are used.

(c) Assumes the power supplies are 99% efficient.

(d) This efficiency is based on total power consumed in the system excluding steady-state coil losses. An equivalent estimate for r/f current drive in tokamaks is $\sim 0.12 A/W$ assuming a conversion efficiency of 0.6.

model indicates that this shell model is least accurate at low coil aspect ratio (the OH-coil self-inductance is over-estimated by a factor of two); an accuracy of better than 20% is obtained for the higher aspect-ratio circuit elements, which account for most of the power dissipation. The algorithms described in Sec. II error conservatively and are of sufficient accuracy for estimating the OFCD reactive power and current-drive efficiency.

The current-drive algorithms were applied to the aforementioned spectrum of air-core RFPs, and the results are summarized in Table I. No steady-state solutions were obtained for ZT-P because the upper and lower bounds on the oscillation period overlap. The current-drive operating window for ZT-P can be opened if τ_R is increased by at least 100 at a driver frequency of 5 kHz; the 5-kHz driver frequency was chosen to obtain an oscillation period that is greater than τ_T and therefore cannot be increased further. A large increase in τ_R for ZT-P can be obtained only by changing the plasma resistance by, for example, decreasing the plasma charge to $Z_{eff} = 1$ and increasing the plasma temperature to $T_e = 2 \text{ keV}$, neither of which are possible. Accompanying a change in the plasma resistance is a change in τ_T as is illustrated in Table I for a two order-of-magnitude decrease in the plasma resistance and, hence, loop voltage. The MHD tearing-time constraint on the oscillation period is violated for such a low loop voltage, and current drive would not be possible.

The ZT-40M parameters and OFCD results for the experiment in which a 5% increase in poloidal flux was observed⁵ are included in Table I. The ZT-40M results are at a relatively low (60 kA) current because higher (180-200 A) current experiments suffered from enhanced plasma-wall interactions (PWI) which increased the plasma resistance and negated any OFCD effect. A divertor that fixes the separatrix during OFCD could minimize PWI effects. Simulation of ZT-40M with the algorithms of Sec. II was not possible because ZT-40M is an iron-core device and requires a different circuit model, but has been simulated in Ref. 5.

The next larger RFP simulated is ZTH operated at $I_p = 2 \text{ MA}$. Driver frequencies which satisfy the period constraints are in the range of 100-200 Hz. A drive frequency of 200 Hz was chosen because 100 Hz produced sufficiently large oscillations to lose reversal at a normalized toroidal-flux swing of $\delta\phi/\phi_0 = 0.035$ used for all devices simulated. Reversed steady-state solutions were obtained at 100 Hz for $0.065 \leq \delta\phi/\phi_0 \leq 0.100$ and at 200 Hz for $0.030 \leq \delta\phi/\phi_0 \leq 0.115$. The upper bound on $\delta\phi/\phi_0$ at both frequencies is set by the maximum oscillation in toroidal flux. The lower bound is set by the upper bound on I_p oscillations and, hence, Θ , which results in a loss of reversal because adherence to an F - Θ curve is required.

The continuous liner in ZTH would dissipate 37 MW and accounts for over half of the entire current-drive power, as

is indicated in Table I. Toroidal and poloidal gaps in the liner reduce the liner dissipation to 30 W. The liner gaps must hold off low toroidal and poloidal electric fields of 0.06 and 0.11 V/m, respectively. The continuous liner also causes substantially larger reactive powers in the OH and TF coils compared to a liner with gaps. The increased OH-coil flux swing couples to the EF coils and overdrives the EF coils so that power must be extracted from the EF coils to maintain steady state. Operation either at higher values of $\delta\phi/\phi_0$, which results in lower amplitude plasma-current oscillations, or with a liner with gaps would eliminate the EF-coil overdrive.

The current and voltage wave forms for ZTH with a continuous liner are shown in Fig. 4. The largest amplitude current oscillation occurs in the TF coils, in which the current also changes direction; the toroidal field at the plasma, however, does not change sign because poloidal currents in the liner and shell maintain a reversed field. A larger value for $\delta\phi/\phi_0$ eliminates the alternating direction of the TF-coil current. The shell currents are larger than the liner currents even though the shell has gaps because the shell is relatively thick (10 mm) and has a non-negligible inductance and a resistance that maximizes the induced current. The TF-coil voltage has a large phase shift ($\sim 73^\circ$) relative to the plasma voltage, V_p , because of the relatively large space between the TF coils and the plasma surface.

The last two RFP devices considered, FTF and TITAN-II, have gaps in the first wall, a 120-MW power savings results for TITAN-II. The drive frequencies for FTF and TITAN-II are low because of the lower loop voltage. The mean values of F are lower than in ZT-P and ZTH (-0.1 versus -0.2, respectively) to minimize the steady-state TF-coil dissipation. Both designs use an EF trim coil to track the equilibrium in order to reduce the reactive power; a 7-GVA reactive power reduction results for TITAN-II. The FTF design has a larger blanket dissipation compared to TITAN-II because different blanket materials result in a 10^6 smaller blanket resistivity for FTF.

IV. CONCLUSIONS

In progressing from present experiments to the commercial reactor, RFPs become larger and require more plasma current to produce increased temperature and confinement time and decreased loop voltage. Associated with increased plasma current is enhanced PWI which may necessitate simultaneous divertor operation with OFCD. The current-drive efficiency empirically scales as $I_p/P_{CD} \propto (2V_p)^{-1}$ which implies that current-drive experiments should become easier as I_p increases and T_e and V_p decrease. However, the maximal current-drive efficiency of $\sim \frac{1}{3} \text{ A/W}$ is achievable only in the reactor regime through the efficient management of the large reactive powers associated with OFCD. The primary means to manage this power is through the use of

Figure 4. The current and voltage wave forms for ZTH with a continuous liner at a driver frequency of 200 Hz.

poloidal and toroidal electrical gaps designed into structures, such as the first wall/liner, in which OFCD induces currents. Insulating gaps, however, create problems associated with field errors, vacuum leaks, and neutron damage. A second power-management technique arises in the case of a coil set with small amplitude oscillations about large steady-state currents. A smaller reactive power is obtained by dividing this coil set into a set (trim coils) devoted to the current oscillation and a second set to produce the steady-state current. The final power-management technique requires the use of high-Q power supplies. Even for $Q_{PS} = 100$ power supplies, which are commercially available, the power-supply dissipation is 30% of the total current-drive power for TITAN-II. The development of a $Q_{PS} = 1,000$ power supply based on room-temperature superconductors would increase the TITAN-II current-drive efficiency to $\frac{1}{2}$ A/W. The

results presented herein demonstrate the potential of OFCD as an efficient method to sustain a steady-state plasma current in RFP reactors. The unambiguous experimental demonstration of OFCD, however, awaits larger devices (e.g., ZTH) capable of higher current and temperature operation and lower loop voltages than are presently possible.

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