Oscillating Field Current Drive in the MST Reversed Field Pinch

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Abstract: Oscillating Field Current Drive (OFCD) is an inductive current drive method which could sustain a DC plasma current without magnetizing flux accumulation. Its application in the reversed field pinch (or possibly other magnetic configurations) could provide the means to sustain a steady-state reactor plasma with Ohmic current drive efficiency. We report MST experiments in which 10% of the plasma current is driven by OFCD. The magnitude of the driven current agrees with theoretical expectations, but interestingly the maximum current does not occur for a relative phasing of the oscillators which produces maximum helicity injection. The OFCD current drive efficiency is 0.1 A/W, which is about the same as that for conventional Ohmic induction. Magnetic fluctuation amplitudes from MHD tearing modes are found to depend on the relative phase, with the minimum amplitudes occurring with maximum current drive.

1. Introduction

Many magnetic fusion configurations rely on current in the plasma to provide at least part of the confining magnetic field. Maintaining a steady-state magnetic field in a fusion reactor is desirable to avoid the technical challenges and additional cost associated with cyclic thermal and mechanical stresses. In the reversed field pinch (RFP), the confining magnetic field is created primarily by plasma current, and only a small portion is provided by pressure-driven bootstrap current (except perhaps at very low aspect ratio). Identifying an efficient steady-state current drive method, or developing an attractive pulsed-current scenario, is therefore essential for RFP development.

Oscillating Field Current Drive (OFCD) is an inductive current drive method which could sustain a DC plasma current without magnetizing flux accumulation. Because the underlying current drive is inductive, the current drive efficiency is expected to be large. To create OFCD, oscillatory (audio-range) toroidal and poloidal inductive loop voltages are applied with a relative phase that is predicted optimum 90 degrees by a simple magnetic helicity balance. OFCD drives current primarily in the outer region of the plasma, which then penetrates into the core via magnetic relaxation associated with MHD tearing instabiity.

We report here experiments in the Madison Symmetric Torus (MST) RFP in which 10% of the plasma current is driven by OFCD [1]. The magnitude of the driven current agrees with theoretical expectations, but interestingly the maximum current does not occur for a relative phasing of the oscillators which produces maximum helicity injection. The OFCD current drive efficiency is 0.1 A/W, which is about the same as that for conventional (steady) Ohmic induction. Magnetic fluctuation amplitudes from MHD tearing modes are found to depend on the relative phase, with the minimum amplitudes occurring with maximum current drive. For poloidal mode m=0 fluctuations, the time-average fluctuation amplitude can be smaller with OFCD than without. These results establish the capability of OFCD to drive a portion of the plasma current, motivating experiments at higher power to produce a larger fraction of current drive by OFCD.

2. Oscillating Field Current Drive Basics

Oscillating Field Current Drive is a form of magnetic helicity injection. Magnetic helicity is defined by the volume integral $K = \int \mathbf{A}\cdot\mathbf{B}\,dV$, where $\mathbf{A}$ and $\mathbf{B}$ are the magnetic vector potential and magnetic field within the plasma volume. Due to its longer characteristic decay time relative to energy dissipation, helicity conservation is expected to constrain relaxed-state plasmas. This motivates helicity balance, in a torus given by

$$dK/dt = 2V_t\Phi_t - 2\int \eta\,\mathbf{J}\cdot\mathbf{B}\,dV \qquad (1)$$

where V_t is the toroidal inductive loop voltage at the plasma surface, Φ_t is the toroidal flux, η is the plasma resistivity, and $\mathbf{J}$ is the plasma current density. The first term on the right hand side represents (inductive) helicity injection, and the second term represents helicity dissipation. Stationary magnetic equilibria satisfy $dK/dt = 0$. For conventional induction, helicity injection is created by the steady Ohmic loop voltage $V_t = I_tR_t$, where I_t and R_t are the toroidal plasma current and resistance. Although the magnetic helicity is maintained constant in the plasma volume by steady induction, a forever increasing transformer poloidal flux is not permitted, and so the inductive pulse length is limited.

Suppose the poloidal loop voltage, $V_p = -d\Phi_t/dt$, and V_t are each sinusoidal with frequency ω and relative phase δ. Then the $2V_t\Phi_t$ term in Eq. 1 yields a dc cycle-average *steady-state* helicity injection rate $v_t v_p \sin(\delta)/\omega$, where $v_{t,p}$ denote the sinusoidal amplitudes [2]. Helicity balance therefore implies purely oscillatory loop voltages are capable of sustaining a dc plasma current. This ac helicity injection scheme is called Oscillating Field Current Drive (and sometimes F- Θ Pumping in older RFP literature). Maximum helicity injection occurs with a relative phase $\delta = \pi/2$ between the two loop voltages. If helicity dissipation does not depend on δ, maximum current drive is also expected for $\delta = \pi/2$. The helicity balance does not specify the appropriate choice of frequency, but helicity conservation is expected only if the plasma remains in a relaxed state. So it is implicit that the OFCD drive frequency should be small relative to the inverse relaxation time scale, e.g., the hybrid MHD tearing time scale.

It is helpful to describe a complementary view on OFCD. Separate the magnetic and (inductive) electric field into their ac and dc components, $\mathbf{B} = \hat{\mathbf{B}} + \overline{\mathbf{B}}$ and $\mathbf{E} = \hat{\mathbf{E}}$, where the "hat" denotes the ac component and the over-line denotes the dc (cycle-averaged) component. For OFCD, the applied loop voltages are purely sinusoidal and $\overline{\mathbf{E}} = 0$. Furthermore, the cycle-averaged Ohm's law is just $\overline{\mathbf{V}\times\mathbf{B}} = \eta\overline{\mathbf{J}}$. The loop voltages produce an oscillating radial pinch velocity $\hat{\mathbf{V}}_r = \hat{\mathbf{E}}\times\mathbf{B}/B^2$ and a parallel-to-$\overline{\mathbf{B}}$ motional emf given by

$$\hat{\mathbf{V}}_r \times \hat{\mathbf{B}} = (\hat{\mathbf{E}} \times \mathbf{B}/B^2) \times \hat{\mathbf{B}} = (\hat{\mathbf{E}} \cdot \hat{\mathbf{B}}/B^2)\overline{\mathbf{B}}. \quad (2)$$

The oscillating pinch velocity beats with the oscillating field to create dc parallel induction, which extends well into the plasma if the oscillating fields penetrate deeply. The physics governing the field penetration has been studied in recent nonlinear, resistive, 3D MHD computational studies at high Lundquist number [3], which demonstrate full current sustainment by OFCD via dynamo-relaxation from MHD tearing fluctuations with amplitudes similar to those calculated in prior studies of steady induction. The radial profiles of the mean-field $\overline{\hat{\mathbf{V}}_\mathbf{r} \times \hat{\mathbf{B}}}$ and fluctuation-induced dynamo $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} \rangle_{||}$ are shown in Fig. 1, as calculated in the MHD simulation. (The lower case **v** and **b** refer to the non-symmetric components of the flow velocity and magnetic field.) The mean-field emf is edge peaked, while the dynamo acts to maintain the current in the core.

A consequence of the ac loop voltages is that the plasma current and magnetic field have an ac component, which modulates the magnetic equilibrium. The size of the ac component scales with the plasma resistance. For example, the normalized ac amplitude of the toroidal current is predicted to scale as $\hat{I}_t/\overline{I_t} \sim S^{-1/4}$, where $S = \tau_R/\tau_A$ is the Lundquist number [3]. The ac amplitude of the toroidal field at the surface is particularly constraining. Empirically, lack of toroidal field reversal causes the plasma resistance to increase markedly. At reactor-like temperatures, the ac modulation is projected to be small. For present-day large RFP experiments, the modulation is not expected to be small, making a full sustainment test very challenging.

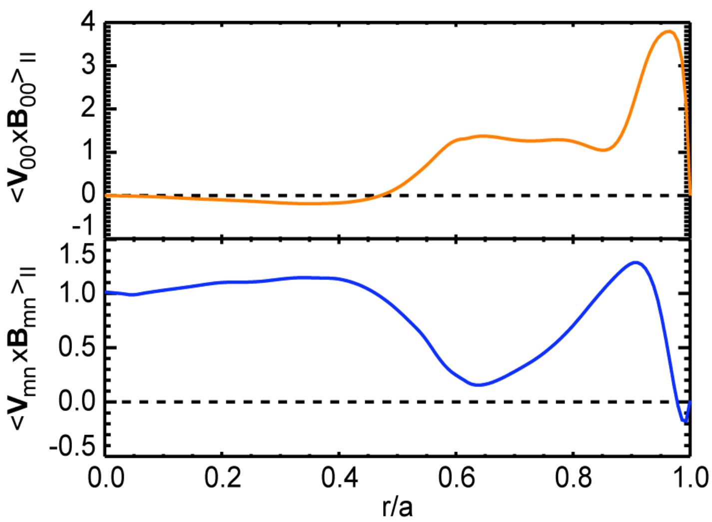

FIG. 1. Top graph shows the radial profile of the cycle average motional emf resulting from the mean-field $\mathbf{V} \times \mathbf{B}$*. The bottom graph shows the radial profile of the MHD dynamo* $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} \rangle_{||}$ *(from [3]).*

3. Partial Current Drive by OFCD in MST

The MST is a large RFP, with major radius R=1.5 m, minor radius a=0.5 m, and plasma current $I_t \leqslant$0.55 MA [4]. To test OFCD, two resonant L-C oscillators are used to produce sinusoidal loop voltages with $\omega/2\pi = 280$ Hz [1]. Each oscillator has ~1 MVA reactive power, and their relative phase is adjustable. The oscillators are not capable of producing full sustainment by OFCD. Instead, they are superposed on background steady induction, and the change in current is measured. Example loop voltage waveforms are shown in Fig. 2. This approach is similar to experiments conducted in the 1980's on the ZT-40M RFP, where $\leqslant$ 5% current drive was produced [5]. Large plasma-wall interaction and increased plasma resistance were believed to limit the OFCD current drive in ZT-40M. The larger size of MST permits smaller loop voltages, related to the S-scaling discussed in [3].

Figure 3 shows the toroidal plasma current for three cases: δ is set to drive current, to anti-drive current, and the reference case with OFCD turned off. For the drive case, a 10% increase in the current by the end of the flattop is measured. The plasma L/R time is longer than the current flattop, so a saturated 15-20% increase would be expected if the pulse and oscillators lasted longer. This amount of added current agrees reasonably well with nonlinear computation of partial OFCD, as well as power balance modeling assuming the plasma maintains a preferred current profile. At maximum current drive, the cycle-average AC input power is $\sim$ 200 kW, so the current drive efficiency for the OFCD-added current is about 0.1 A/W, the same as for the background steady induction. For fixed oscillator voltages, the magnitude of the added current does not appear to depend on the magnitude of the background current, as might be expected. Of course the percentage current drive is smaller if the background current is larger.

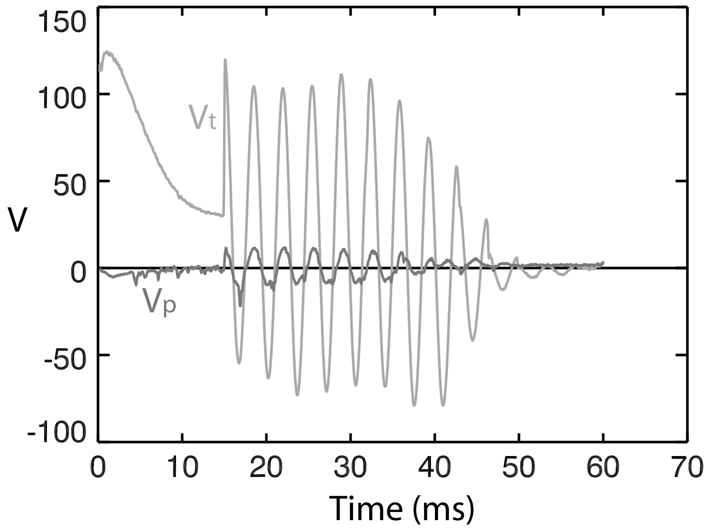

FIG. 2. Toroidal and poloidal loop voltages for OFCD experiments in MST. Their relative phase is adjusted by varying the turn-on time of the V_p oscillator.

The helicity balance in Eq. 1 predicts that the OFCD-added current should vary as $\sin(\delta)$. Operating the oscillators with different phases produces a rough sinusoidal variation, but not quite as expected, as shown in Fig. 4(a). In particular, the added current is maximum for $\delta \approx \pi/8$. The amplitudes of m=0 and m=1 magnetic fluctuations are observed to be phase dependent as well, shown in Figs. 4(b) and 4(c). To illustrate the time dependence, Fig. 5 shows the mode amplitudes for the case with relative oscillator phasing $\delta = 5\pi/8$. The m=0 and m=1 fluctuations are from resonant tearing modes, which underlie the MHD dynamo-relaxation process and increase

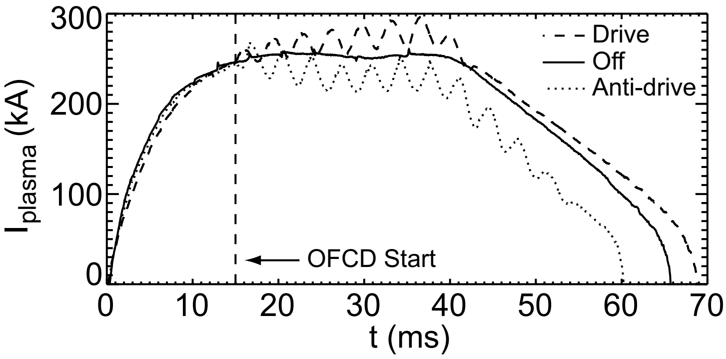

FIG. 3. Plasma current for OFCD oscillator phasing set to drive current, anti-drive current, and the reference case with OFCD turned off.

heat transport by generating magnetic stochasticity. The phase at which these fluctuations are smallest is the same as for maximum driven current.

In normal RFP plasmas (without OFCD), the *m*=0 fluctuations arise by nonlinear coupling to the linearly unstable *m*=1 modes [6]. Their amplitudes burst sharply at sawtooth crash events, as seen in Fig. 5(d). Between sawtooth crashes, they have small amplitudes. With OFCD, in addition to the sawtooth burst, the *m*=0 modes can grow large between crashes as in Fig. 5(c). This occurs during the portion of the loop voltage cycle when the electric field at the edge is directed to increase the current. We speculate that the current profile may be steepened in the edge region near the *q*=0 surface, and the *m*=0 modes become linearly unstable. This is phenomenologically similar to the increased *m*=0 seen in Pulsed Poloidal Current Drive (PPCD) experiments when the applied poloidal loop voltage is large [7].

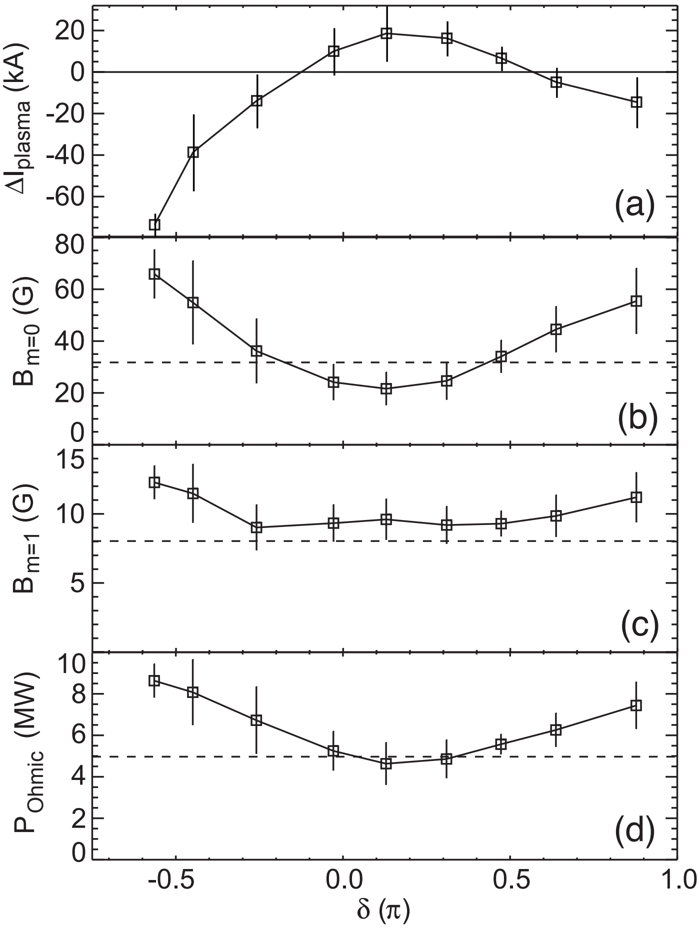

FIG. 4. Dependence of (a) change in plasma current, (b) m=0 amplitude, (c) m=1 ampltiude and (d) Ohmic input power as a function of the relative oscillator phase, δ. The dotted lines indicate the OFCD off reference values.

A robust, new behavior with OFCD is that the sawtooth cycle entrains to the loop voltage oscillations, as seen in Fig. 5. With OFCD off, the sawtooth crashes occur quasi-periodically. With OFCD on, the sawtooth crashes always occur near the end of the portion of the loop voltage cycle when the electric field at the edge is directed to oppose the current in the edge region. At this time the electric field is tending to increase the global peakedness of the current profile, likely destabilizing the core-resonant *m*=1 modes and triggering the sawtooth crash. (Note that this is the “anti-PPCD” phase of the cycle.)

The Ohmic input power (combined OFCD and steady induction) depends on the oscillator phasing, as shown in shown in Fig. 4(d). This is a similar trend as for the fluctuation amplitudes. It is probable that the increased tearing fluctuations cause a decrease in the electron temperature and therefore decreased plasma conductivity. (Thomson scattering measurements are in progress.) Thus, a modest confinement change associated with the varying MHD tear-

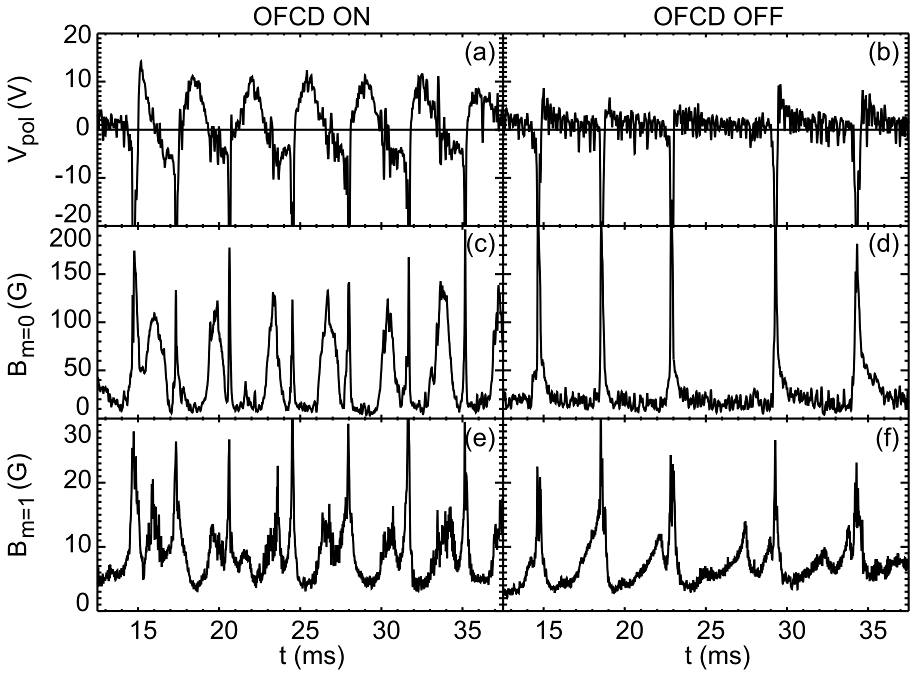

FIG. 5. *Time dependencies for $\delta = 5\pi/8$ with OFCD on and off: the poloidal loop voltage (a) on and (b) off, the m=0 amplitude (c) on and (d) off, and the m=1 amplitude (e) on and (f) off. The sharp spikes seen it all quantities occur at the times of sawtooth crash events, which become entrained to the loop voltage oscillations when OFCD is applied.*

ing amplitude could be responsible for the distorted (nonsinusoidal) phase dependence. Cyclic variation of the current profile that depends on the phase could also be important. Note that the m=0 amplitude is actually smaller for $\delta \sim 0$ compared to standard RFP operation with steady induction. Also, the increase in the fluctuation amplitudes is greatest for anti-drive phasing. This could explain the larger percentage change (decrease) in plasma current for anti-drive phasing.

4. Summary

Partial OFCD in MST is seen to increase the current by 10%, with a current drive efficiency consistent with Ohmic induction. The amount of current drive is consistent with predictions from nonlinear MHD computation. The MHD tearing fluctuation amplitudes are observed to depend on the relative oscillator phasing, smallest for the phase which produces maximum current. Maximum current does not occur at $\delta = \pi/2$. This could result from phase-dependent current profile modifications, causing phase-dependent magnetic helicity dissipation. Or it could result from a confinement response to the tearing fluctuation amplitudes, affecting the electrical conductivity.

These results establish the capability of OFCD to drive a portion of the plasma current, and motiviate experiments at higher power for larger fraction current drive by OFCD. The oscillators are currently being upgraded to test larger fraction current drive. Because tearing fluctuations can cause the magnetic field to become stochastic, energy confinement is linked to current sustainment [8]. A key question for OFCD is whether or not simultaneous good confinement can be achieved. MST's recently improved diagnostic capability will be used to assess the confinement properties during OFCD.

Acknowledgment

This work was supported by the US Department of Energy and the National Science Foundation.

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