Oscillating-Field Current-Drive Experiments in a Reversed Field Pinch

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Oscillating-field current drive (OFCD) is a steady-state magnetic helicity injection method to drive net toroidal current in a plasma by applying oscillating poloidal and toroidal loop voltages. OFCD is added to standard toroidal induction to produce about 10% of the total current in the Madison symmetric torus. The dependence of the added current on the phase between the two applied voltages is measured. Maximum current does not occur at the phase of the maximum helicity injection rate. Effects of OFCD on magnetic fluctuations and dissipated power are shown.

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Various types of current sustainment for toroidal laboratory plasmas are forms of magnetic helicity injection. Helicity $K = \int \mathbf{A} \cdot \mathbf{B} d\nu$ is the total linkage of flux of the magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$ in the plasma volume ν. Helicity constrains relaxed states due to its approximate time invariance [1–4], and relates to the toroidal plasma current through the poloidal flux, which links toroidal flux in general. The time derivative in a torus can be written $dK/dt = 2V_t\Phi_t - 2\int \eta \mathbf{J} \cdot \mathbf{B} d\nu$, which suggests magnetic helicity injection as current drive. The first term on the right represents inductive helicity injection with a toroidal loop voltage V_t and toroidal flux Φ_t, as in the standard (or "steady") toroidal induction used for the reversed field pinch (RFP) [5]. Helicity injection is applied to balance the helicity dissipation, due to the resistive electric field $\eta\mathbf{J}$, represented by the last term.

Oscillating-field current drive (OFCD) [6–8] is a type of steady-state, inductive helicity injection (sometimes called $F - \Theta$ pumping or ac helicity injection). In OFCD, sinusoidal toroidal and poloidal loop voltages $\nu_t \sin(\omega t - \delta)$ and $\nu_p \sin\omega t$ are applied. The poloidal voltage leads to an oscillating toroidal flux with amplitude ν_p/ω, and so the cycle-averaged inductive helicity injection rate is $\nu_t\nu_p \sin\delta/\omega$. Since an ac voltage has zero cycle average, OFCD sustainment is steady state (unlike toroidal induction), which would make it well suited to compact RFP reactor designs with high mass-power density [9]. Also it is expected to have Ohmic current-drive efficiency, driving the bulk electron distribution [10]. 3D MHD calculations [11,12] indicate OFCD is capable of sustaining all the current in an RFP.

The sinusoidal loop voltages induce symmetric oscillations in the plasma pinch velocity and magnetic field. The resulting electromotive field drives edge current with a radial gradient leading to MHD tearing instability. The helical, tearing fluctuations in flow and field, $\mathbf{u}$ and $\mathbf{b}$, cause magnetic relaxation through an electromotive field $\langle \mathbf{u} \times \mathbf{b} \rangle$ (or "dynamo") which acts to flatten the current profile, transporting current from the edge to the core.

Two chief issues for OFCD are the dynamics of the current penetration by magnetic relaxation and the effect of the relaxation on plasma energy confinement. While the presence of the fluctuations implies possibly detrimental effects on confinement [13,14], recent calculations [12] show their amplitudes are not much different than for toroidal induction.

In this Letter we report that OFCD has been used to produce about 10% of the total plasma current in the Madison symmetric torus (MST) [15] RFP (see Fig. 1). The dependence of the current on the relative OFCD phase is measured, and notably the maximum current does not occur at the phase of maximum helicity injection. Magnetic fluctuation amplitudes are also found to depend on the phase, and the maximum current occurs with the minimum amplitudes. Compared to toroidal induction alone, the time-average poloidal mode $m = 0$ fluctuation amplitudes are smaller at the maximum OFCD current, as is the total dissipated power, implying in this case that the OFCD need not degrade confinement, and could actually be improving it. We also observe that the relaxation process is entrained to the applied oscillations. The OFCD current-drive efficiency is about 0.1 A/W, about the same as that for the toroidal induction. Previously, OFCD was used to drive about 5% of the current in the ZT-40M RFP [16]. However, the detailed phase dependence and effect on MHD tearing activity were not investigated in that case.

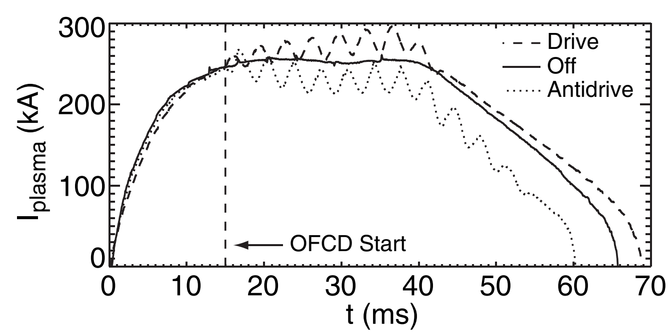

FIG. 1. Time dependences of the plasma current for three different pulses. The dashed curve is for the OFCD drive case, the dotted curve is for the OFCD antidrive case, and the solid curve is for the case with OFCD turned off.

Also, OFCD has been attempted in tokamak devices, without conclusive, positive results [17,18].

Figure 1 shows the measured plasma current for three MST pulses, where OFCD is set to drive positive current, where it is set to drive negative current (or "antidrive"), and where OFCD is off. The observed additional plasma current (whose fractional increase is about the same as that for the magnetic helicity) is limited to about 20 kA by reactive impedance, since the 20 ms pulse provided by the OFCD power supplies is shorter than the plasma's L/R time of about 30 ms. If both the OFCD and MST pulses were much longer than this L/R time, then a saturated plasma current addition of about 40 kA could be expected.

The global electromagnetic quantities during the OFCD pulse are shown in Fig. 2. The ac voltages are provided by a pair of pulsed, switched tank circuits inductively coupled to the main MST loop voltage circuits. The tank circuits are tuned to have the same resonant frequency $f \approx 280$ Hz and are triggered separately to control the phase δ between the two voltages. Referring to Fig. 2, note that the toroidal loop voltage oscillation ν_t and the toroidal flux oscillation ϕ_t, both with frequency f, are responsible for the OFCD helicity injection, whose rate has both a $2f$ component and a nonzero cycle average. Incidentally, using either single oscillator alone results in neither net helicity injection nor an increase in plasma current.

Both the measured helicity injection rate and input power for OFCD display roughly the expected sinusoidal dependences on δ, as it is varied from pulse to pulse for a phase scan, as shown in Fig. 3. The measured ν_t and ϕ_t give a cycle-averaged rate of helicity injection $\langle 2\nu_t\phi_t\rangle$. Note the helicity ejection phases show larger magnitude than the injection phases due to the changed plasma load and finite output impedance of the power supplies. Also, the plasma toroidal current oscillation i_t and toroidal-magnetic-field-winding current oscillation i_p with the voltages give a cycle-averaged OFCD input power $\langle i_t\nu_t + i_p\nu_p\rangle$.

Maximum plasma current does not occur at the maximum helicity injection rate. Figure 4 shows the OFCD-produced plasma current for different values of δ. The most positive current is observed for $\delta \approx \pi/8$, while the highest injection rate occurs for $\delta \approx \pi/2$. As expected, there is a strong decrease in current for $\delta \approx -\pi/2$, where the helicity ejection rate is maximum. These results imply that the helicity dissipation in OFCD both depends on δ and is not proportional to the injection. The current peak was also not observed at $\delta = \pi/2$ in 3D MHD calculations [12,19], a result of the large helicity dissipation at the maximum injection phase.

Magnetic tearing fluctuations and relaxation are strongly affected by the applied OFCD waveforms. The amplitudes of the tearing modes are modulated at the OFCD frequency, as seen in Fig. 5. Magnetic relaxation in the standard RFP occurs through a quasiperiodic, sawtooth relaxation cycle, with core-to-edge current transport occurring at the sawtooth crashes, indicated by the large voltage spikes in Fig. 5. The natural sawtooth cycle duration depends on the relaxation time [20]. However, in OFCD the relaxation is entrained to the applied oscillations.

Amplitudes of $m = 1$ core-resonant modes increase noticeably between sawteeth, while the amplitudes of the edge-resonant $m = 0$ modes increase more strongly, and both are clearly modulated at the OFCD frequency. The crash amplitudes are somewhat smaller with OFCD, and the crash events themselves are now strictly periodic, entrained to the OFCD cycle. This effect and the $m = 0$ modulation are likely due to the modulation of the edge current profile by the oscillating voltages while the $m = 1$ modulation may involve more complicated, nonlinear effects.

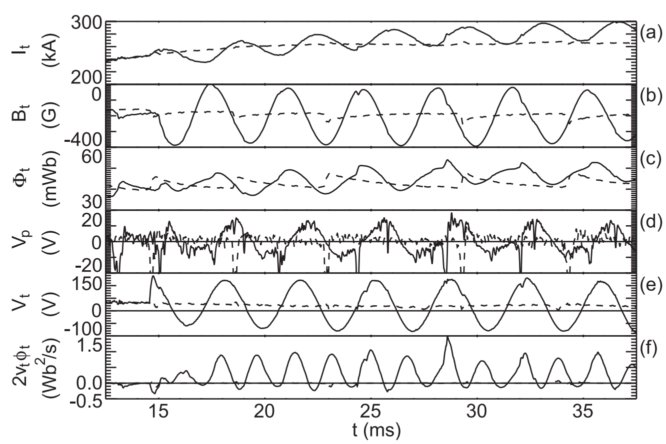

FIG. 2. Time dependences of (a) plasma toroidal current, (b) edge toroidal magnetic field, (c) total toroidal flux, surface (d) poloidal and (e) toroidal loop voltages, and (f) rate of helicity injection due to oscillating components of toroidal voltage and flux. Solid curves are for OFCD on and dashed curves are for OFCD off.

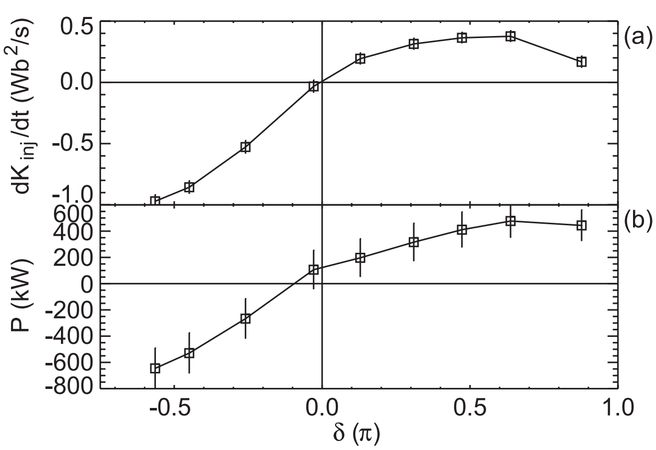

FIG. 3. Phase dependences of the cycle-averaged OFCD (a) helicity injection rate $\langle 2\nu_t\phi_t\rangle$ and (b) input power $\langle i_t\nu_t + i_p\nu_p\rangle$ (derived from the measured ac quantities). Error bars indicate pulse-to-pulse variability.

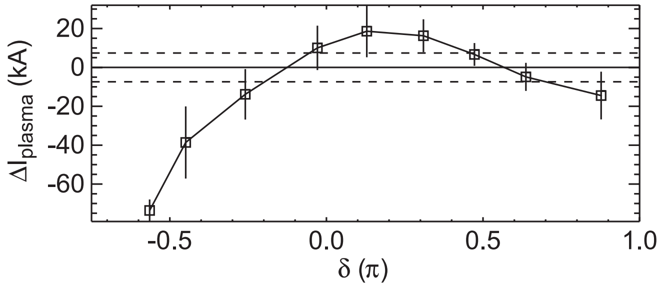

FIG. 4. Phase dependence of the change in cycle-averaged plasma current at the end of OFCD, relative to the change for OFCD off. Error bars refer to pulse-to-pulse variation in the measured current change. The two horizontal dashed lines show the pulse-to-pulse variation in measured current change for the same time period with OFCD off.

The change in fluctuation amplitudes depends on phase. Figure 6 shows the cycle-averaged mode amplitudes for different δ's. The amplitudes are larger than those for OFCD off at the phases for which the magnitude of the OFCD helicity injection rate is largest, positive or negative. For δ's near the plasma current maximum the change in amplitude is smaller, and the $m = 0$ mode amplitude is actually somewhat smaller than for the OFCD-off case.

The total input power and Ohmic power (i.e., from both OFCD and toroidal induction) are minimum at the plasma current maximum, as shown in Fig. 7. The input power is the cycle average of the total Poynting flux into the plasma, calculated from measured surface quantities. The Ohmic (i.e., dissipated) power is the input power minus the rate of change of magnetic energy calculated from a fit of the measured magnetic data to a relaxed state equilibrium model [20]. The phase dependence of these quantities is similar to that for the fluctuation amplitudes, which is consistent with the understanding that energy confinement tends to increase as tearing amplitudes decrease, thus lowering the Ohmic input power. Incidentally, in MST there is no strong indication of severe plasma-wall interactions during OFCD.

Overall, the OFCD results seem to be the combined effects of helicity injection physics and confinement physics. What seems to result in the most positive plasma current is a combination of positive helicity injection with smaller magnetic activity, not just one or the other. Changes in the Ohmic power and mode amplitudes are

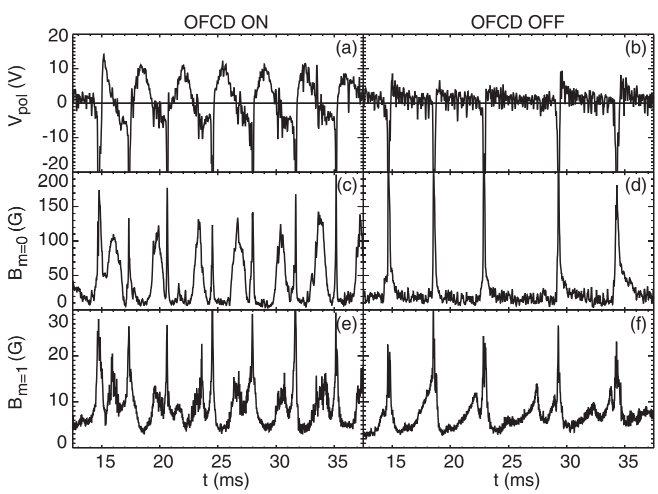

FIG. 5. Time dependences of the poloidal loop voltages for $\delta \approx 5\pi/8$ OFCD (a) on and (b) off, $m = 0$ (toroidal modes $1 \leq n \leq 4$) tearing mode amplitudes for (c) on and (d) off, and $m = 1$ ($6 \leq n \leq 15$) amplitudes for (e) on and (f) off.

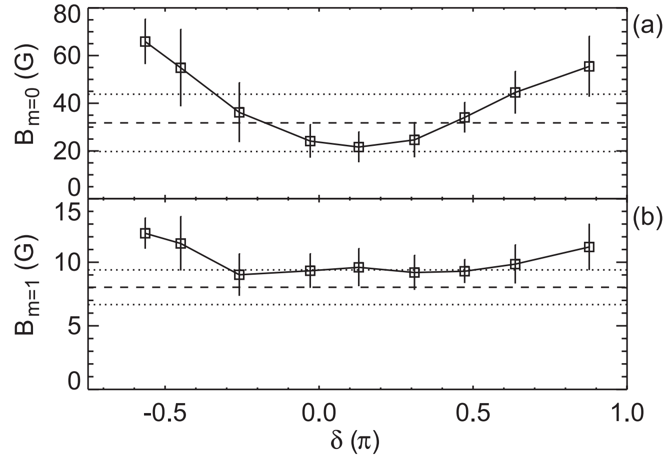

FIG. 6. Phase dependences of cycle-averaged (a) $m = 0$ ($1 \leq n \leq 4$) mode amplitude and (b) $m = 1$ ($6 \leq n \leq 15$) mode amplitude during the OFCD pulse. Error bars indicate pulse-to-pulse variability. Dashed horizontal lines are the same respective averages for OFCD off, and dotted lines indicate pulse-to-pulse variability for OFCD off.

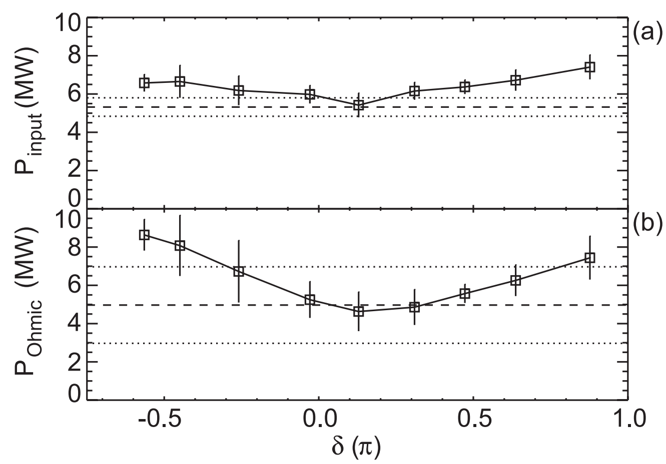

FIG. 7. Phase dependences of cycle-averaged, total (a) input power, i.e., the Poynting flux, and (b) the Ohmic input power, i.e., the input power minus the rate of change of magnetic energy from a relaxed state model, during the OFCD pulse. Error bars indicate pulse-to-pulse variability. Dashed horizontal lines are the same respective averages for OFCD off, and dotted lines indicate pulse-to-pulse variability for OFCD off.

relatively small for a broad range near the maximum current-drive phase, including phases where the current drive is small or even negative. So, current drive generally tracking helicity injection is expected. However, at the same time the decreased mode activity could allow higher plasma conductivity, permitting increased current from the background toroidal induction. The possibility of partial OFCD for fluctuation control has already been proposed in MHD theory [21], and a single oscillating voltage has been used for that purpose in RFP experiments [22].

It is likely that the observed phase dependence is related to the respective time scales for helicity injection and magnetic relaxation. The OFCD period must not be much smaller than the characteristic magnetic relaxation time scale [12]. For the RFP the relevant relaxation time is probably the natural sawtooth cycle period. For the plasmas tested the sawtooth period is about the same as the OFCD period. Therefore, the plasma may be not completely relaxing, and so an increased injection may be countered by an increased dissipation, through edge currents associated with tearing modes.

The information on plasma magnetic activity and confinement presented here is based on surface measurements, but a complete picture requires time-varying internal profiles of magnetic field, temperature, and density, and such work will be reported in the future.

In summary, OFCD is observed to produce about 10% of the total plasma current in MST with about the same current-drive efficiency as toroidal induction. The current maximum does not occur with the maximum helicity injection rate ($\delta = \pi/2$), but at a smaller phase with positive helicity injection at which the OFCD-modulated magnetic fluctuations and the total dissipated power are smallest. Contributions to the plasma current by the OFCD helicity injection itself and by the inferred confinement changes during OFCD both appear to be important, although their relative contributions are unknown.

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