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Oscillating Field Current Drive Studies for the Reversed Field Pinch

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Oscillating field current drive (OFCD) is tested experimentally in the Madison Symmetric Torus (MST)) and modeled theoretically. In OFCD two AC loop voltages are applied at the edge of the plasma to drive a DC plasma current. Preliminary results from recent OFCD partial current drive experiments indicate a net mean current drive consistent with expectation. The applied AC magnetic fields of OFCD modulate magnetic fluctuation amplitudes and affect general MHD phenomena. Some observations indicate cyclic anomalous ion heating sharing the frequency of the applied field. MHD calculations including full 3D nonlinear simulations predict that OFCD could fully sustain an RFP at plasma parameters achievable in the laboratory. The calculated plasma current includes a large oscillating component whose amplitude decreases with the plasma resistivity. The periodic deep reversal of the calculated edge toroidal field destabilizes a large edge-resonant mode not typical of an Ohmically driven RFP. However the other characteristic RFP modes are not significantly larger during OFCD in the simulation.

Introduction

Oscillating field current drive [1] is a method of steady-state equilibrium sustainment for the reversed field pinch (RFP) [2]. In OFCD poloidal and toroidal AC loop voltages with common frequency ω and phase difference δ are applied at the plasma edge. Then the cycle-averaged rate of magnetic helicity injection is $(V_p V_t \sin\delta)/\omega$, where V_p and V_t are the respective voltage amplitudes. Thus the two AC voltages can interact to drive a mean plasma current. In ZT-40M experiments OFCD generated about 5% of the total plasma current [3]. The frequency ω should *not* satisfy $\omega\tau_{relax}>>1$, where τ_{relax} is the plasma hybrid relaxation time, so that the driven currents fully penetrate the discharge. Also ω *should* satisfy $\omega\tau_R>>1$, where τ_R is the plasma resistive diffusion time, in order to avoid extreme periodic changes in the magnetic profile [4].

We report on experiments in MST and then describe MHD theory work on OFCD, followed by a short summary.

Experiments

In MST OFCD is tested using two oscillator circuits coupled inductively to the RFP; one circuit applies an AC toroidal loop voltage V_t~100 V and the other applies an AC poloidal loop voltage V_p~10 V. Each is composed of an LC tank circuit fed by a pulse-forming network, switched by a commutating ignitron feedback system, and pre-chargeable to begin a pulse at full voltage. Each OFCD circuit applies ~1 MVA reactive power and ~100 kW input power to the MST plasma, compared to 2-5 MW input power applied during a typical MST pulse without OFCD. Partial current drive has been tested using two different OFCD frequencies, ~500 Hz and ~250 Hz. Since τ_{relax}~1 ms and τ_R~1 s for MST, both of these frequencies are roughly consistent with the criteria above.

In a typical experiment the RFP is first formed and sustained with a flat top by the MST Ohmic current drive, and then OFCD is added. For different pulses the phase difference δ is varied to compare driven current with helicity injection rate. Such a comparison is shown in Figure 1, which is a preliminary result for OFCD at ~250 Hz. About 15 kA mean plasma current in addition to the ~250 kA Ohmic current is driven by OFCD in this example, with a few 10's of kA negative drive when the OFCD circuits are phased for anti-drive. The ~5% OFCD-driven current is roughly consistent with simple power balance arguments, relaxed-state modeling, and MHD numerical calculations [5].

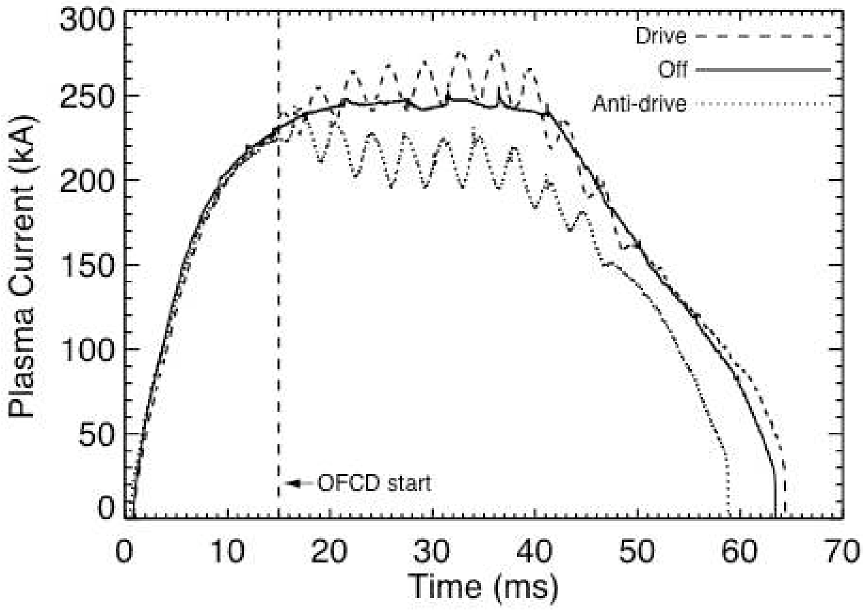

Figure 1. Partial OFCD current drive results at 250 Hz in MST indicate a small mean OFCD plasma current in addition to the normal Ohmically driven current.

However at higher frequency mean current drive has not been reproducible, perhaps because then $\omega\tau_{relax}$ is too large. Indeed, experiments at ~500 Hz to detect magnetic field penetration showed little or no penetration in most cases.

The applied AC loop voltages in OFCD tend to modulate MHD activity, and entrain the otherwise quasi-periodic sawtooth relaxation cycle. Also, some observations with only an applied AC poloidal loop voltage indicate cyclic anomalous ion heating. Figure 2 shows majority ion temperature (T_i) results obtained from a Rutherford scattering diagnostic, plotted along with amplitudes of magnetic fluctuations with poloidal mode numbers m=0 and m=1 and the applied AC voltage. In these data a T_i oscillation proceeds with the same AC frequency as do the other signals. There is also a spike in T_i at the single sawtooth event shown. Ion Doppler spectroscopy also shows an oscillation in impurity ion temperature. As both features of the temperature signal are correlated with mode amplitudes it is plausible that an electromagnetic heating mechanism is responsible for the ion heating. Not all similar experiments have shown the same ion temperature oscillations.

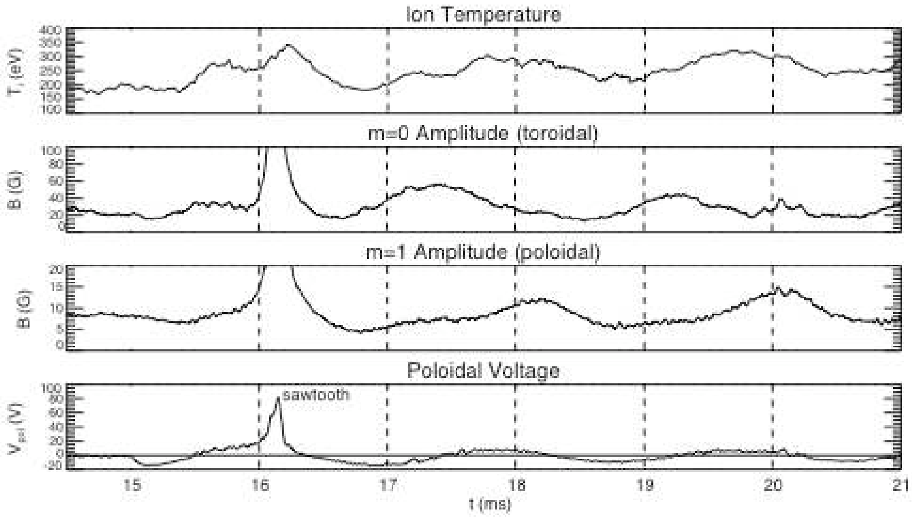

Figure 2. Majority ion temperature, mode amplitudes, and applied AC poloidal loop voltage. The applied voltage results in an ion temperature oscillation.

Theory

Three-dimensional resistive MHD calculations are used to model an RFP fully sustained by OFCD [6]. These predict that OFCD can sustain an RFP at $S=10^5$, where the Lundquist number S is the ratio of τ_R to the Alfven time and gauges the importance of magnetic relaxation over resistive diffusion. An AC toroidal plasma current I_{AC} is superimposed on the DC toroidal plasma current I_{DC} and at $S=10^5$ these two are about equal. The toroidal field reversal parameter F is also modulated drastically, a notable effect being the linear destabilization of an edge-resonant mode, external to the reversal surface, which is not typical of an Ohmically sustained RFP. This edge mode is significantly larger than the core modes, although these themselves are not much larger with OFCD than without.

Companion calculations have $S=5\cdot10^5$ thus modeling a less resistive plasma, and here I_{AC}/I_{DC} is reduced to ~50%, as shown in Figure 3. This is consistent with one-dimensional relaxed-state modeling predicting $I_{AC}/I_{DC}\propto S^{-1/4}$. The F modulation also decreases with larger S. MST has S~10^6 or larger, and a reactor value would be even larger again. Since the edge mode instability is due to the F modulation that decreases with larger S, one could expect that at larger S values this edge mode would become less significant or nonexistent.

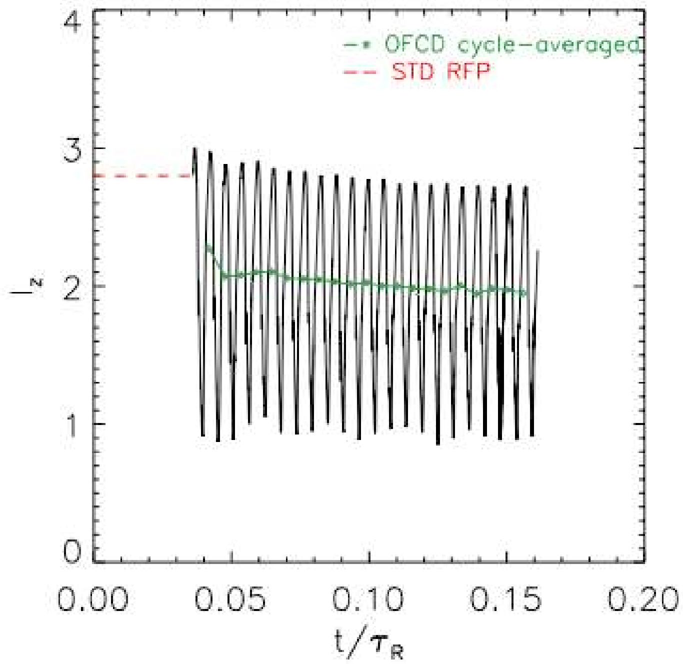

Figure 3. Three-dimensional resistive MHD calculation at $S=5\cdot10^5$ models the RFP toroidal plasma current fully sustained by OFCD.

Summary and Future Work

To date experiments in MST indicate a small net plasma current driven by OFCD of about 5% of the background RFP current. These tests are scheduled to continue at both ~250 Hz and ~500 Hz frequencies while new diagnostics will be used to study internal effects like confinement and magnetic relaxation. MHD calculations have shown that OFCD can fully sustain an RFP with a large modulation that decreases with larger *S* values. In about one year an improved OFCD system will be installed on MST for use at higher power.

References

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