Oscillating Field Current Drive Experiments in the Madison Symmetric Torus

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Oscillating Field Current Drive (OFCD)

- A toroidal current drive method possible for reversed field pinch (RFP) sustainment
- Applied oscillating loop voltages with induced fluctuations to drive net plasma current

**Advantages:**
- Steady-state
- Inductive
  - Efficient since drives bulk electron distribution
  - Requires no electrodes

**Main issues:**
- Dynamics of current drive
- Effect of fluctuations on plasma energy confinement
**OFCD Injects Helicity to Sustain Plasma Current**

- Magnetic helicity is total linked flux
  \[ K = \int \mathbf{A} \cdot \mathbf{B} \, dv \propto \Psi \Phi \]
- Helicity injection to sustain current
  \[ \frac{dK}{dt} = 2V_t \Phi_t - 2\int \eta \mathbf{J} \cdot \mathbf{B} \, dv \]

**OFCD:** (Bevir & Gray, 1981)

- Toroidal and poloidal AC loop voltages
  \[ V_t = v_t \sin(\omega t - \delta) \]
  \[ V_p = v_p \sin \omega t \]
- Get oscillating toroidal flux
  \[ \Phi_t = \frac{v_p}{\omega} \cos \omega t \]
- Time-averaged helicity injection rate
  \[ \langle 2V_t \Phi_t \rangle = \frac{(v_t v_p}{\omega} \sin \delta \]

- OFCD used to drive extra plasma current in ZT-40M RFP
  (Schoenberg et al., PoP 1988)
MHD Calculations Show Full RFP Sustainment, OFCD Dynamics

- Recent 3D, nonlinear, MHD calculations show OFCD capable of full RFP sustainment (Ebrahimi et al., PoP 2003)
- Magnetic fluctuation amplitudes about the same as in standard RFP
  - Largest is helical $m=1$ outside reversal surface at edge, linearly unstable due to large equilibrium modulation
- Required modulation decreases with Lundquist number $S (= \tau_{\text{resistive}}/\tau_{\text{Alfven}})$

\[ E + V \times B = \eta J \]

- OFCD directly drives net \( <V_{00} \times B_{00}> \) at edge from symmetric oscillations
- Helical magnetic tearing fluctuations produce net \( <V_{mn} \times B_{mn}> \) effect to drive current in core
OFCD Tested in MST Reversed Field Pinch

- ~ 10% net added to plasma current
- Ohmic current drive efficiency
- Maximum plasma current not at maximum helicity injection
- Magnetic fluctuations modulated and entrained by OFCD
- $m=0$ fluctuation amplitudes reduced in OFCD maximum plasma current case compared to standard RFP case
- Current profiles modulated by OFCD
- OFCD as MHD control tool; ion heating example
Inductively Coupled OFCD Tank Circuits Provide Two AC Loop Voltages to MST

- Total OFCD power $\approx 2.0$ MVA reactive
- OFCD power input to MST $\leq 500$ kW

Madison Symmetric Torus (MST)

$R_0 = 1.5$ m, $a = 0.5$ m RFP

- For OFCD experiments reported, MST background input power $\sim$ several MW
OFCD Adds ~ 10% to Total Plasma Current

- Added plasma current ≤ 20 kA
  - Limited by OFCD pulse length < $L/R$ for MST plasma
  - Limited by OFCD source voltage

- Ohmic current drive efficiency
  ~ 0.1 A/W

- Added current roughly constant at different baseline plasma currents with same OFCD source voltage
Maximum Plasma Current Not at Maximum Helicity Injection

- OFCD phase $\delta$ between applied voltages varied pulse-to-pulse for scan
- Time-average helicity injection rate roughly sinusoidal with $\delta$
- Cycle-average added plasma current maximum at positive helicity injection rate smaller than maximum rate
  - Must be more helicity dissipation at the maximum helicity injection rate

At maximum plasma current:
- $m=0$ mode amplitudes decreased from OFCD-off case
- $m=1$ mode amplitudes near minimum
- Total (steady induction + OFCD) ohmic (dissipated) power decreased from OFCD-off case
- Conclusion: Both OFCD helicity injection and inferred improved confinement with higher conductivity for background steady induction lead to the observed added current
Magnetic Fluctuations Modulated and Entrained by the OFCD Cycle

- Sawtooth magnetic relaxation cycle in standard RFP quasi-periodic
- In OFCD sawtooth cycle entrained to oscillating voltage cycle
- $m=0$ modes (resonant near edge) modulated between sawteeth
- $m=1$ modes (largest of which resonant in core) also modulated but more similar to standard RFP case
Maximum Current OFCD Case Has Minimum Magnetic Fluctuations

- Both OTCD (toroidal oscillation only) and OPCD (poloidal oscillation only) have their own MHD stabilization and destabilization phases.

- Operation with either OTCD or OPCD separately modulates $m=0$ roughly out of phase with the other case.

- Phase ($\delta \approx \pi/8$) of maximum plasma current OFCD case is near superposition of two voltages above, and gives reduced $m=0$ amplitudes.

(Calculations of OFCD to control MHD fluctuations, Ebrahimi & Prager, PoP 2004)
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FIR Faraday Rotation and Motional Stark Effect (MSE) Measurements with Equilibrium Reconstruction Provide Time-Varying Current Profiles
OFCD Current Profile Modulation Leads to Modulation of Magnetic Fluctuation Amplitudes

- AC voltages in OFCD alternately tend to peak, then flatten current profile
- Parallel current profile (flatness parameter $\alpha$) fluctuates with both the background sawtooth relaxation cycle and the cycles of the OFCD voltages
- Cyclic OFCD effect on profiles and magnetic fluctuations depends on $\delta$
OFCD Provides MHD Control Tool for Study of Relaxation Physics, e.g. Anomalous Ion Heating

- Expect anomalous ion heating (*i.e.* faster than possible by electrons) during periods of large magnetic fluctuations

Two beam-based $T_{\text{ion}}$ measurements:

1. CHERS (charge-exchange recombination spectroscopy) for impurity ions

2. Rutherford scattering for majority ions

- Both measurements show small cyclic OFCD heating (between sawteeth) for maximum plasma current case

- Probably have larger ion heating at other OFCD phases, with larger magnetic fluctuations
Conclusions

• Oscillating field current drive a steady-state, inductive helicity injection method capable of sustaining the RFP, according to MHD calculations
• In MST experiments OFCD adds ~ 10% to total plasma current with ohmic current drive efficiency
• Maximum OFCD current is not at maximum helicity injection, but at smaller, positive helicity injection
• At maximum OFCD current in MST tests, $m=0$ fluctuation amplitudes and total dissipated power reduced from standard RFP case, implying a confinement improvement and higher conductivity for background toroidal induction
• OFCD also used as MHD control tool for other physics studies

Future work:
• More internal profile studies versus OFCD phase
  • Profile MHD behaviors, e.g. $\langle \mathbf{V} \times \mathbf{B} \rangle$ effect for magnetic relaxation
  • Thomson scattering profiles to study electron heating, confinement
• Increase OFCD voltages for more injection
• Increase OFCD pulse duration > $L/R$ toward saturated, steady state with more plasma current