Penetration of AC Fields in MST

The Madison Symmetric Torus (MST) can be operated with applied AC voltages in the poloidal or toroidal direction, or both. Applying both voltages phased $\pi/2$ apart is magnetic helicity injection, and is called oscillating field current drive (OFCD). Applying only the poloidal voltage is called oscillating poloidal current drive (OPCD). The applied voltages result in AC magnetic fields at the surface of the reversed field pinch (RFP).

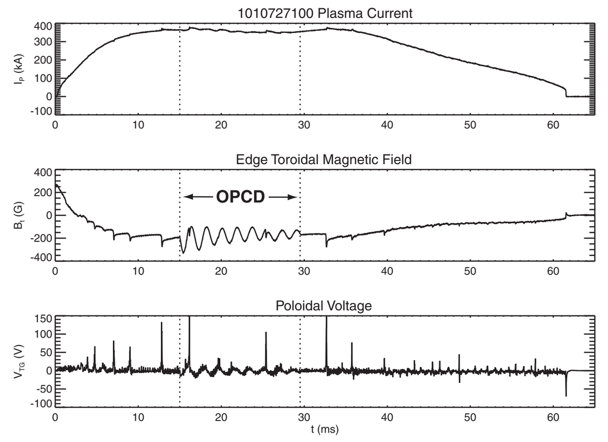
One focus of this work is the study of the penetration of such AC fields into the MST plasma. Using internal magnetic diagnostics, like motional Stark effect (MSE) spectroscopy and far-infrared (FIR) polarimetry and interferometry, field attenuation and phase delay is measured within MST. Experimental results for OPCD are compared to 3-D MHD simulation code output. Another focus of this work is OFCD operation in MST, and such initial experimental results are shown.

It is found that sawtooth relaxation activity plays an important role in modifying AC field penetration phenomena. Toroidal magnetic field fluctuations penetrate the edge region with some phase delay, but they only reach the MST core with the aid of sawteeth. The MHD simulations show qualitative agreement with these experimental results, though all of the relevant code parameters do not match experimental conditions.

MST Operated with OPCD

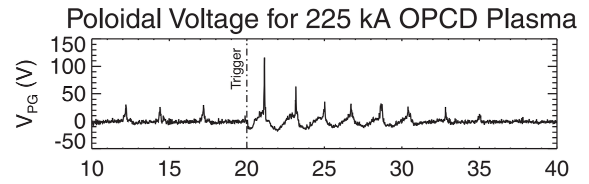
OPCD is achieved with oscillator tank circuit in MST's B_t circuit

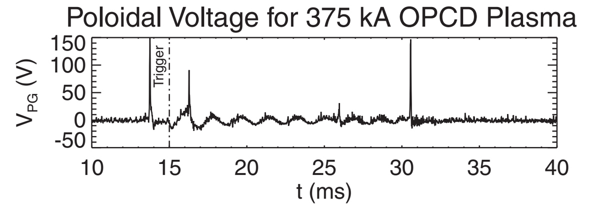
Tank circuit operates at f ~ 550 Hz (τ_{relax} ~ $1/\omega$ << $\tau_{L/R}$):



OPCD does not affect DC plasma toroidal current significantly
OPCD is poloidal current drive
AC part of **E x B** is small in the RFP
So plasma-wall interactions are small
So effect on plasma resistance is small

OPCD Effect on Sawteeth Studied in MST





Sawtooth relaxation period entrained to OPCD cycle
OPCD is edge poloidal current drive
So affects RFP current profile
So affects dynamo activity

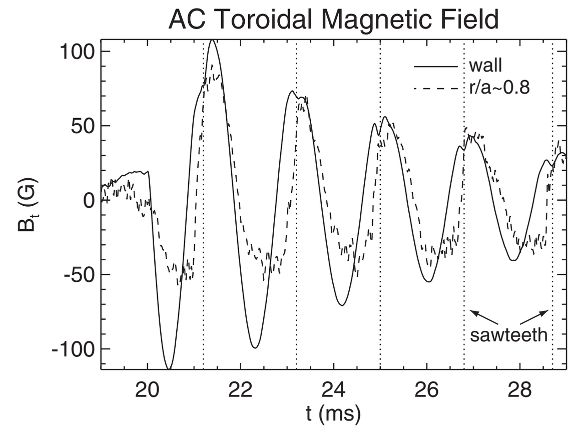
Sawteeth occur near peaks of OPCD poloidal anti-current drive
Then OPCD is tending to cause dynamo activity

OPCD sawtooth period increases with Lundquist number S
Resistive diffusion governs average sawtooth period in an RFP
OPCD enforces regularity in otherwise pseudo-random period

Internal Probe Array Shows Sawtooth Events Aid AC Toroidal Magnetic Field in Penetrating Edge

Edge array has B_t probes every 1 cm from 5 cm to 10 cm depth

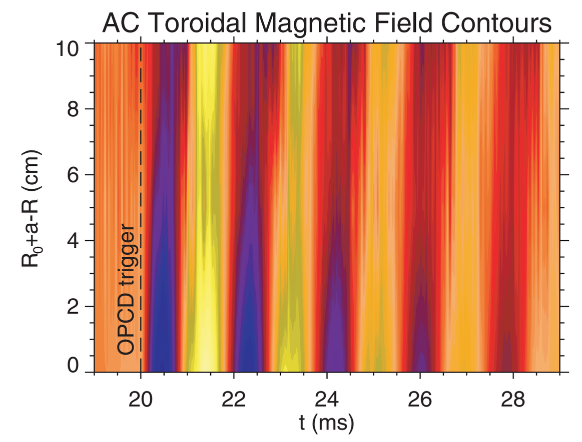
Here MST is operated at low current (I_p < 200 kA) with OPCD



Just before sawtooth AC toroidal field penetrates more slowly and is more attenuated, compared to the opposite behavior just after sawtooth event

Thus sawtooth relaxation event aids field penetration into edge region

Internal Probe Array Shows AC Toroidal Magnetic Field Penetrates with Phase Delay in Edge Region



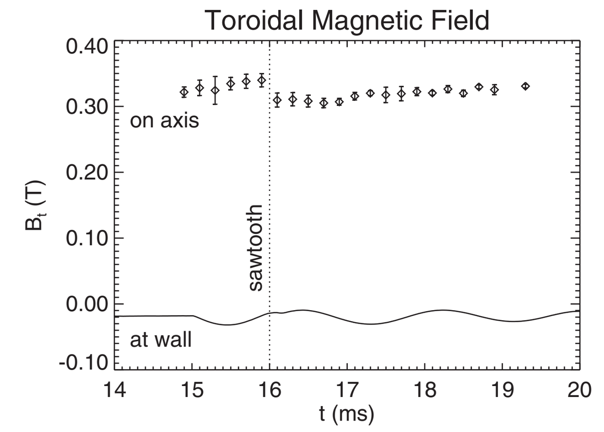
Phase delay at 10 cm (r/a ~ 4/5) is about 100 μs ~ τ_{relax} for MST edge region

MSE Shows Sawtooth Event Aids AC Toroidal Magnetic Field in Penetrating to Core

MSE spectrometer measures Stark effect line-broadening for emission from neutral beam at a single point for a single time, giving B_t at MST core

Reproducible pulse experiments provide MSE time history

Here MST is operated at medium current (I_p ~ 375 kA) with OPCD



AC toroidal field delayed ~ 1 ms ~ τ_{relax} in travel to core during sawtooth

MST core appears shielded from AC field penetration long after sawtooth

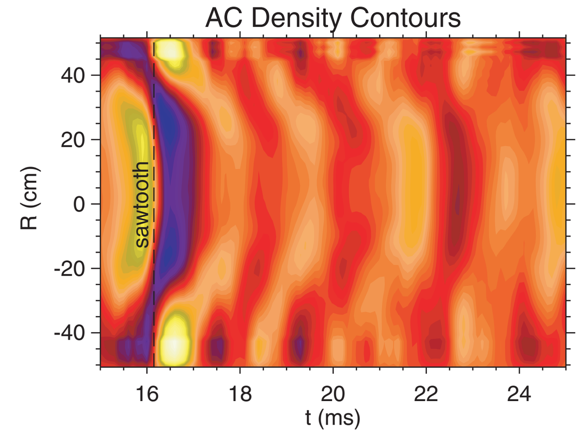
Thus sawtooth event is necessary to allow AC toroidal magnetic field penetration of the RFP core

FIR Interferometry Shows OPCD Density Fluctuations Reach Core without Aid of Sawteeth

FIR multi-chord array provides time-resolved density profiles for MST

Here MST is operated at medium current (I_p ~ 375 kA)

Nine similar pulses without sawteeth between 17 ms and 25 ms averaged

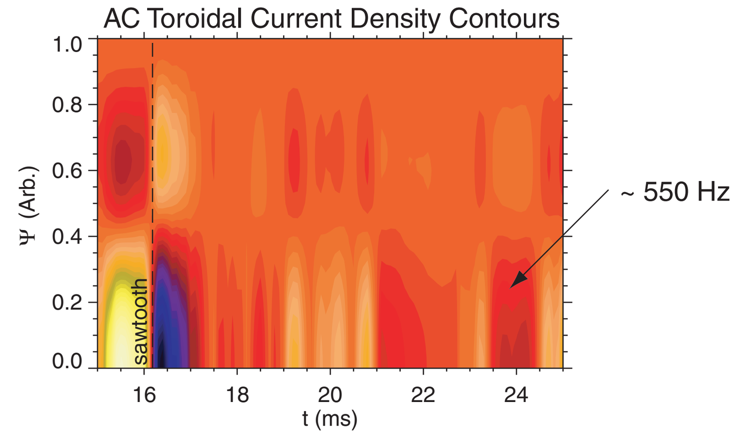


OPCD-induced density fluctuations reach core long after sawtooth event
Sawtooth appears to effect particle transport differently than B_t transport

Phase delay in penetrating edge region ~ 2 ms ~ τ_{relax}

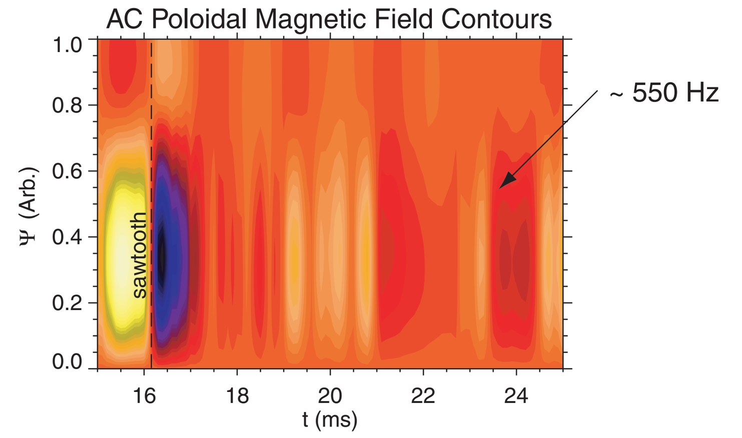
FIR Polarimetry Suggests AC Toroidal Current Reaches Core without Aid of Sawteeth

FIR multi-chord array provides time-resolved B_p profile, assuming $[1-(r/a)^2]^{\alpha}$ profile and density profile from similar MST pulses, which gives J_t profile



Some signal at core shares OPCD frequency long after sawtooth event
Sawtooth seems to effect J_t transport in RFP differently than B_t transport

FIR Polarimetry Suggests AC Poloidal Magnetic Field Reaches Interior without Aid of Sawteeth

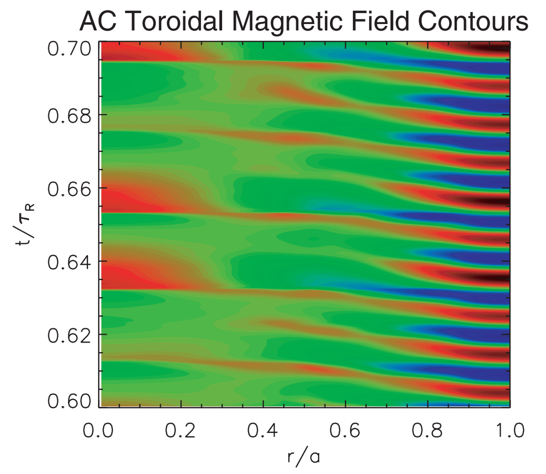


Some signal at interior shares OPCD frequency long after sawtooth event
Sawtooth seems to effect B_p transport in RFP differently than B_t transport

3-D MHD Simulations Consistent with MST Experimental Results for OPCD

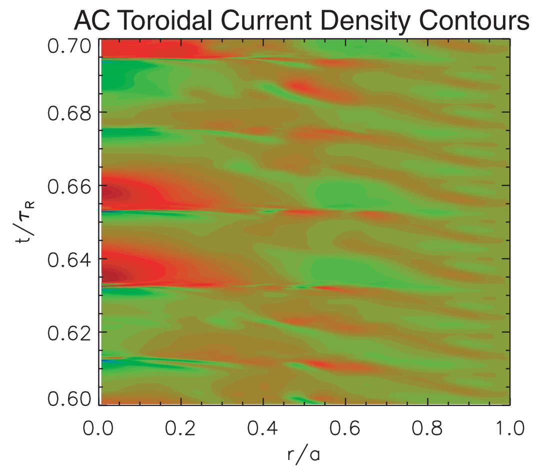
DEBS code uses semi-implicit algorithm with resistive single-fluid MHD equations to model RFP evolution in cylindrical geometry

OPCD run has S = 10^5 (experiment has S > 10^6)
and T_{OPCD} = $1000\tau_A$ (experiment has T_{OPCD} > $2000\tau_A$)

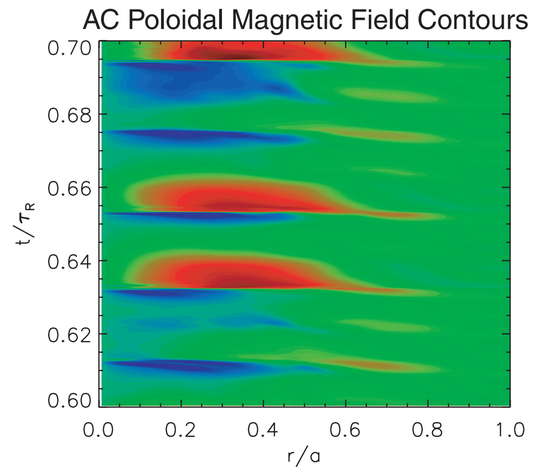


Sawtooth-like activity concurrent with attenuated OPCD signal at core
So code is consistent with medium current MSE results for MST core

OPCD toroidal field penetrates to (r/a) ~ 3/4 with phase delay ~ τ_{relax}
So code agrees with probe array results for low current MST edge region



Toroidal current signals sharing OPCD frequency appear throughout RFP
So code is consistent with FIR results for medium current MST pulses



Poloidal field signals sharing OPCD frequency appear within RFP
So code is consistent with FIR results for medium current MST pulses

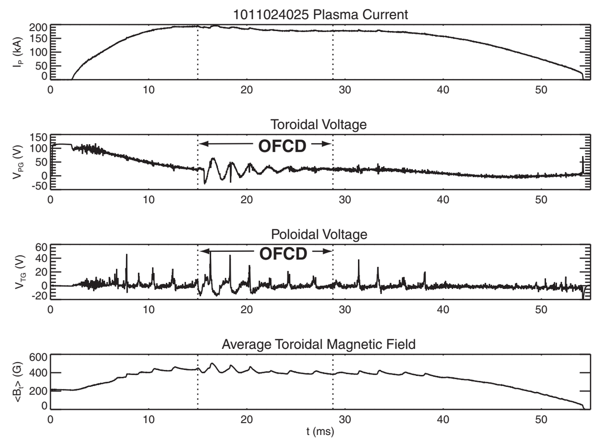
Summary for AC Field Penetration in the RFP

Sawtooth relaxation activity acts to transport toroidal magnetic field energy from core to edge, and vice versa, the latter having been shown here via MST experiments with internal diagnostics in tandem with the OPCD 'probing' method. In the absence of sawteeth, this transport is sharply curtailed within the high temperature RFP and is confined to the edge region. Finally, these experiments show that poloidal magnetic field energy and particle density transport can occur in the RFP by processes not dependent on sawtooth activity.

Future work with AC field penetration in MST will exploit improved MSE and FIR diagnostics, continuing equilibrium reconstructions, and corroboration with MHD theory. Using applied AC magnetic fields is a productive method of study that brings together novel experimental tools and theory in plasma physics.

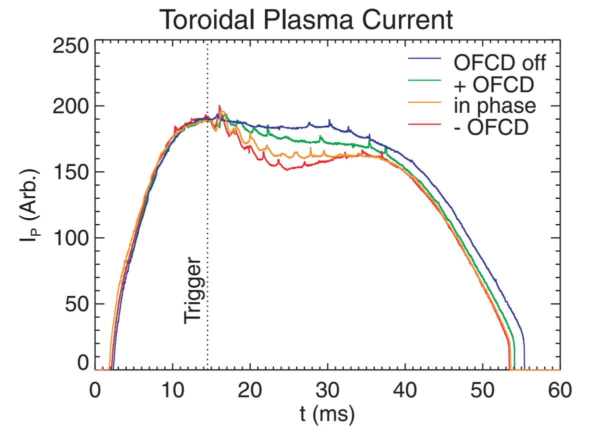
Initial OFCD Operation in MST

OFCD is done with oscillators in B_p circuit and in B_t circuit phased $\pi/2$ apart



Evidence for OFCD Helicity Injection Found in MST

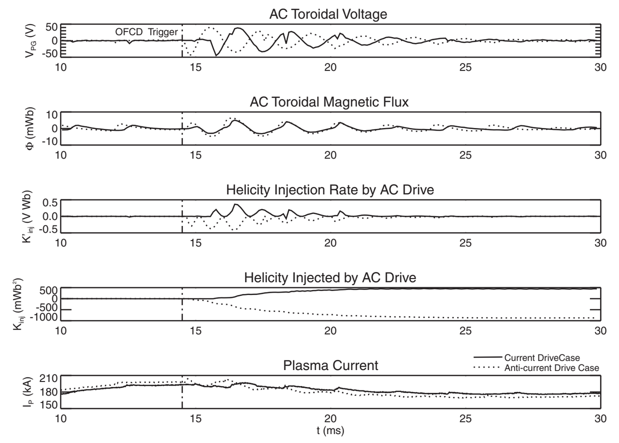
Four different types of pulses produced with similar initial plasma currents:
1) **No OFCD (normal RFP)**
2) **Positive OFCD magnetic helicity injection (+$\pi/2$ phase difference)**
3) **Neutral OFCD magnetic helicity injection (zero phase difference)**
4) **Negative OFCD magnetic helicity injection (-$\pi/2$ phase difference)**



OFCD helicity injection K' competes with wall interactions in the RFP
AC part of **E x B** is not small in the RFP
So plasma-wall interactions are not small
So effect on plasma resistance R is not small

Effect of OFCD K' ~ 1/2 effect of increased R in initial MST experiments
Maybe improved in higher plasma current pulses
Maybe improved by adjusting voltages, frequency
Maybe improved by adding small graphite limiter

Net Change in MST Plasma Current Ascribed to Phases and Magnitudes of AC Parts of Magnetic Helicity Injection Terms



Summary of Initial OFCD Operation in MST

The first OFCD experiments on MST showed the basic magnetic helicity injection effect, along with the intrinsic plasma-wall interaction effect. Much work remains, such as refining the two tank circuits for longer drive duration, experiments with excellent plasma conditions, internal magnetic measurements, optimization of OFCD parameters, and modern MHD studies of related phenomena. It may yet prove possible to do better than Ohmic drive for the RFP with steady state OFCD magnetic helicity injection in MST.