

# **Low power Oscillating Field Current Drive experiments in MST \***

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# ABSTRACT

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Oscillating Field Current Drive (OFCD) is a proposed method of steady state current sustainment in a plasma by application of two oscillating voltages, 90 degrees out of phase, to the toroidal & poloidal circuits. We have developed a 700 kW oscillator installed in the toroidal field circuit of the Madison Symmetric Torus. Investigation of the plasma response to this toroidal-only excitation is underway. A similar oscillator for the poloidal circuit is under construction to allow a 700 kW test of OFCD.

# OUTLINE

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- Ignitron based medium power oscillator design for OFCD
  - Designed, built, & tested one oscillator with MST.
  - Inexpensive solution for mid–power applications.
  - 700 kW peak/30 kW avg power achieved with prototype.
  - Numerous design enhancements for improved power and reliability.
- Experimental Data (with Bt oscillator only) shows:
  - Power delivered to plasma.
  - Sawtooth instabilities are entrained by oscillations
  - Core–resonant  $m=1$  mode amplitude responds to flux injection/anti–injection phase of oscillation.
- High Power ( $\sim 1\text{MW}$ ) tube based oscillators being built.
  - see Adney, et. al. this session

# Oscillating Field Current Drive

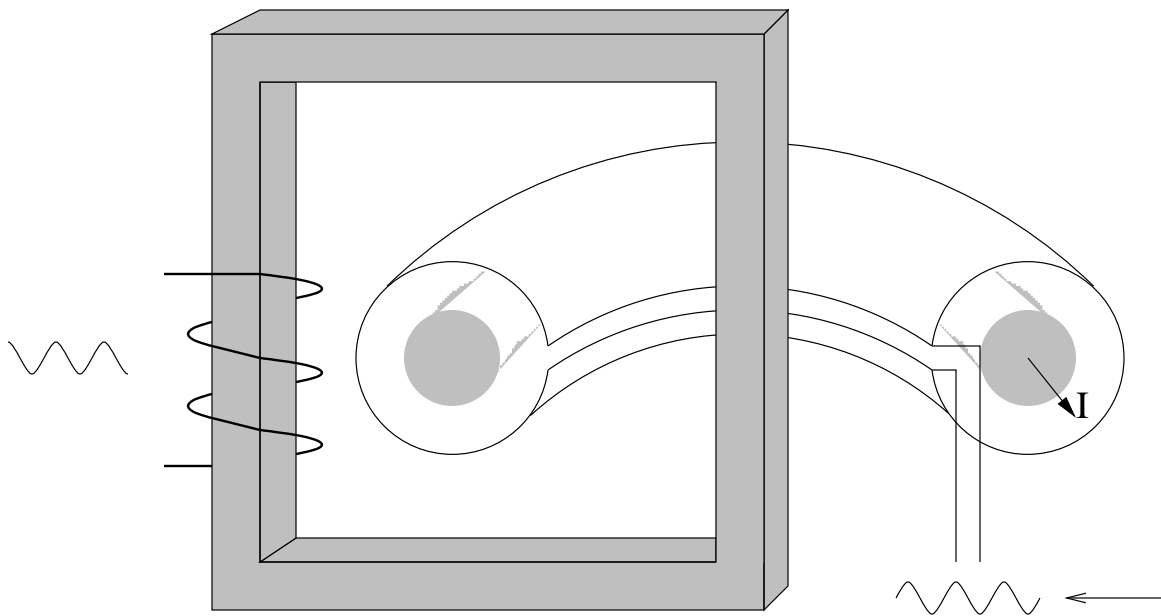
What is it:

A method of generating a sustained plasma current by applying two sinusoidal voltages  $90^\circ$  out of phase to the poloidal and toroidal circuits.

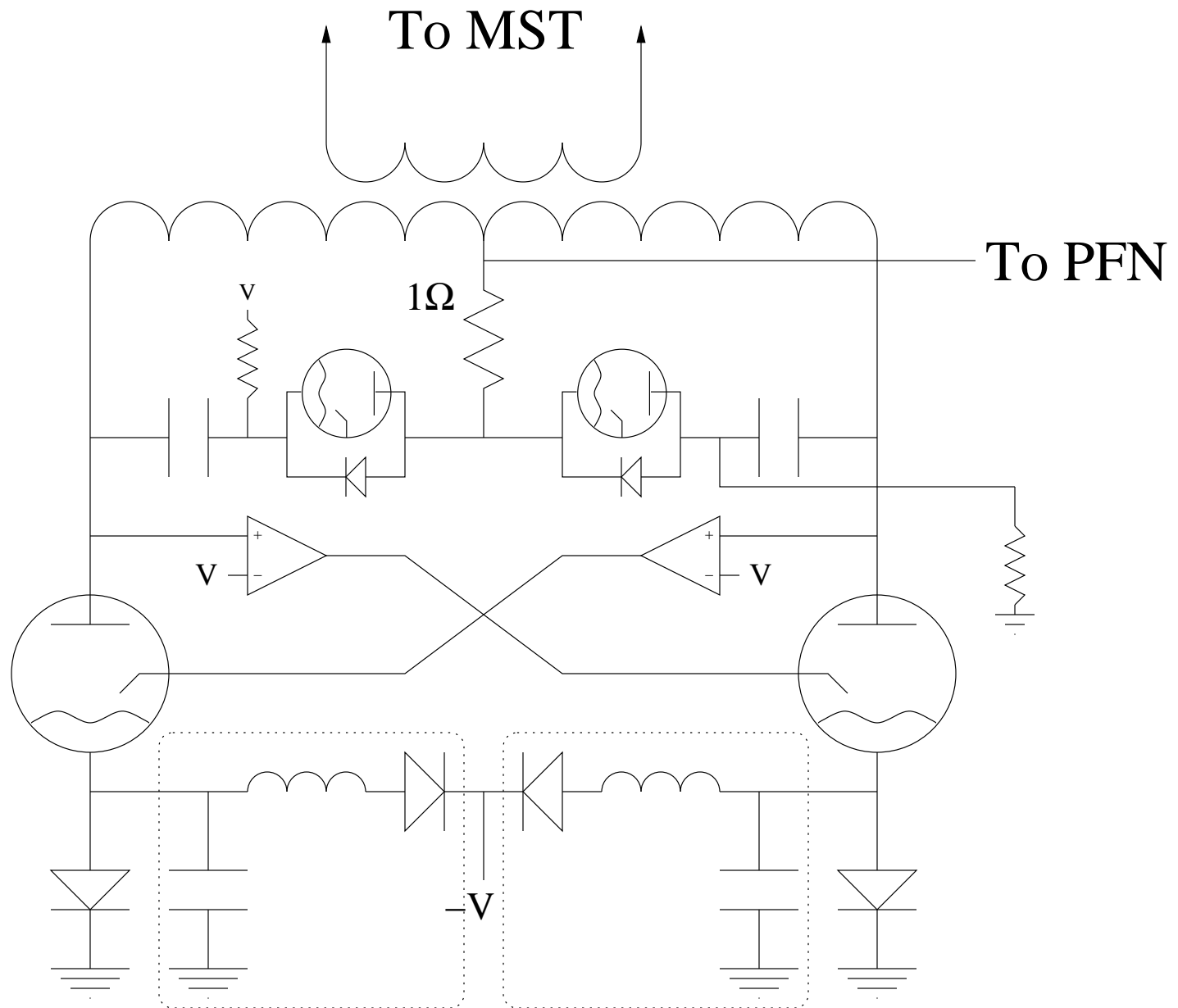
Rectification of oscillating currents is byproduct of conservation of global magnetic helicity.

Frequency for MST plasmas 100–1000 Hz.

**Only toroidal oscillator currently implemented**



# Hybrid Oscillator/Amplifier

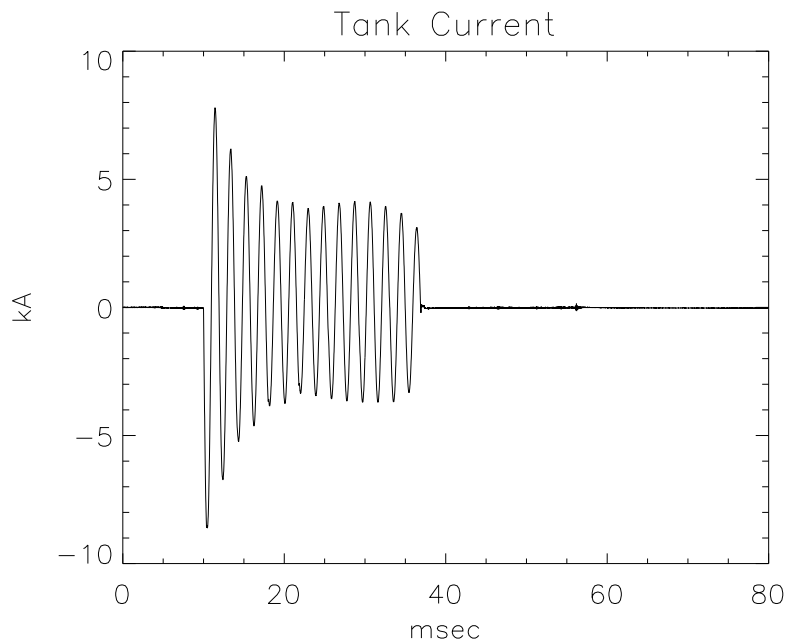


# THE EXPERIMENTS

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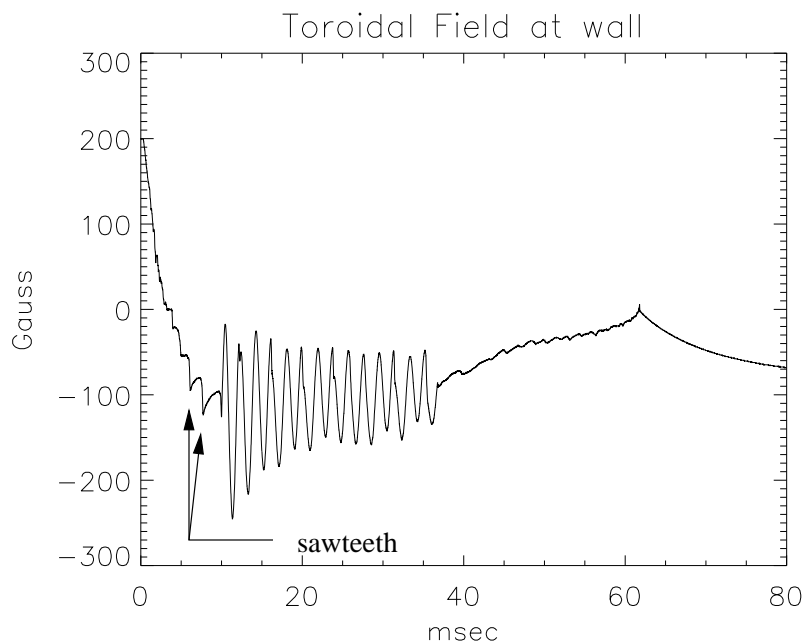
- Goal was to generate/study oscillation with plasma.
- Variables included power, plasma density, & circuit variations.
- Performed tests at 520 Hz
  - Best performance so far is 700 kW peak/30 kW avg into the plasma
- Circuit variations have included:
  - Splitting the tank circuit
    - Unclear why circuit works better with 1 ohm resistor
  - Paralleling ignitrons for more current
    - No trouble synchronizing ignitors
  - Magnets on the ignitrons
    - Significantly improved turn-off time
  - Tank precharge circuit so first cycle is at maximum amplitude
    - Fixed problem of oscillator startup associated with tight coupling to noisy toroidal field circuit.
    - Largest improvement in reliability
  - Feedback from tank to ignitron timing
    - Significantly improved reliability

# Bt OSCILLATION



## Oscillator output

- Shows a well defined pulse. Maximum power achieved on first cycle.
- Pulse width = 14 cycles

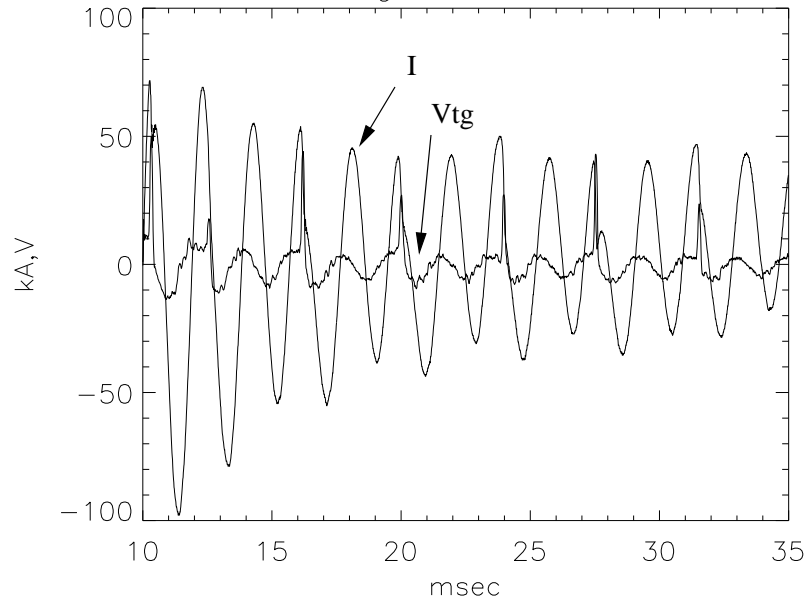


## Toroidal Field Perturbation

- Oscillation is evident on  $B_{\text{toroidal}}$  measured at the wall.
- Oscillator is triggered after reversal has occurred.
- Oscillation is significant perturbation compared to sawteeth.

# POWER & RESISTIVE LOADING

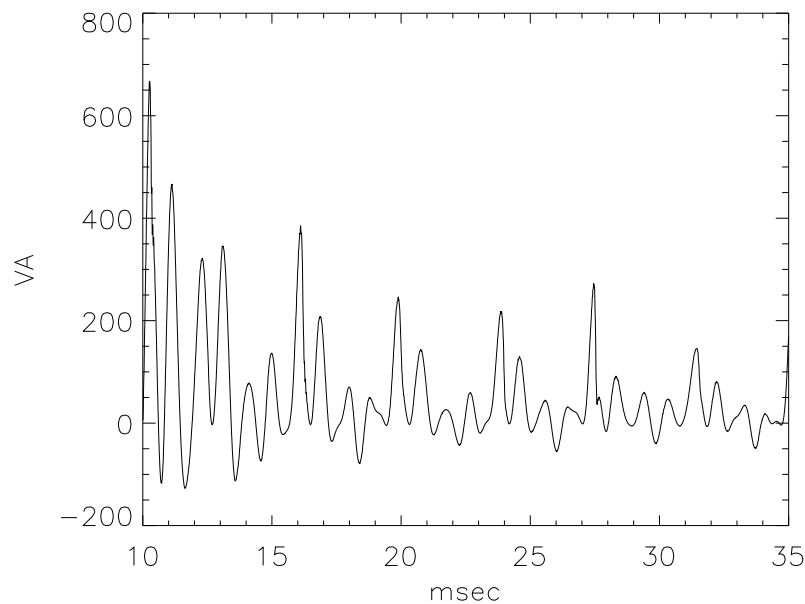
Voltage and Current



## I and V

- Shows magnet current and voltage measured at toroidal gap
- Noise in V measurement due primarily to sawteeth instabilities.

Instantaneous Power

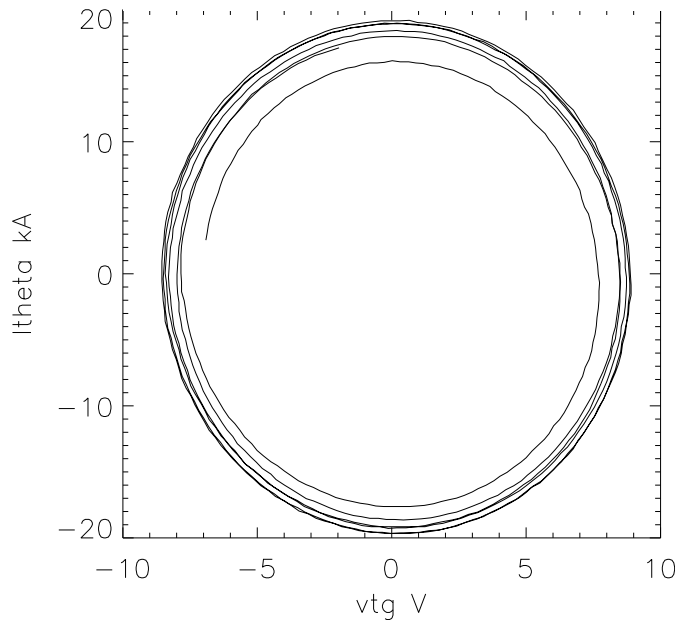


## Instantaneous Power

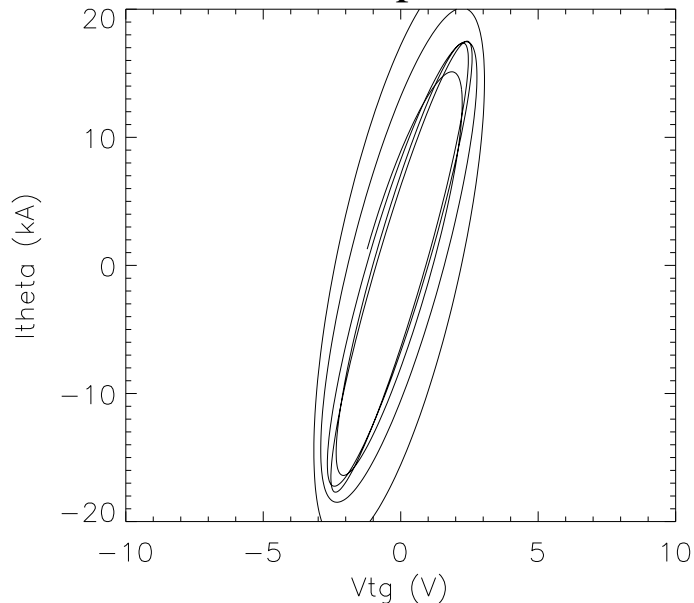
- Shows instantaneous power delivered to plasma.
- Average power = 30 kW
- Peak power = 700 kW

# LISSAJOUS PLOTS

I vs V – no plasma

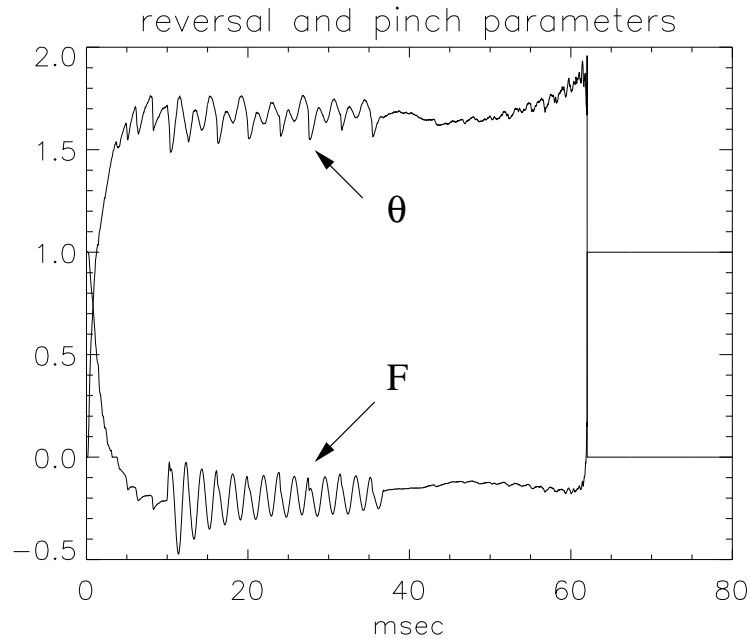


I vs V – with plasma – filtered



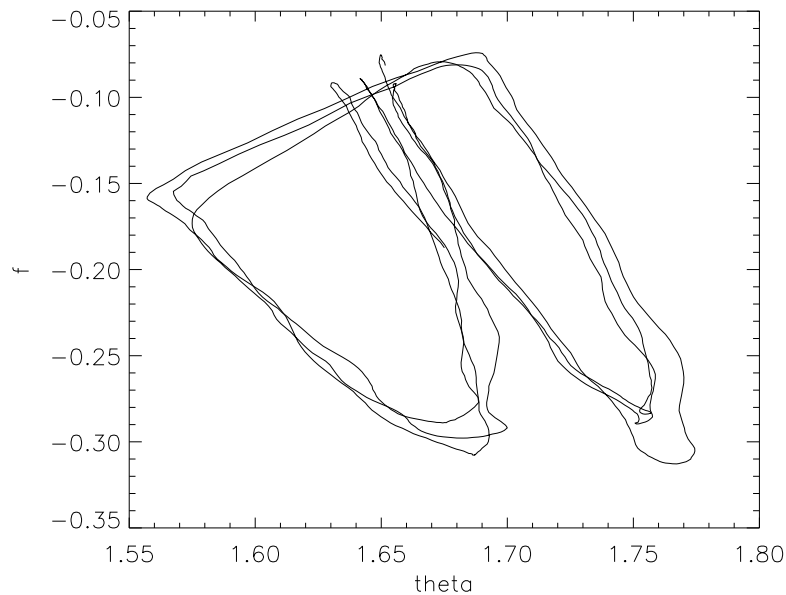
- Lissajou's Diagrams show how reactive a load the plasma presents to the oscillator.
- In a purely reactive load, I & V are 90 out of phase. I vs V is an ellipse or circle with no skew. No power is absorbed.
- Vacuum is a perfect example.
- In a purely resistive load I & V are in phase and I vs V is a straight line. All power is absorbed.
- For a load with reactive and resistive components I vs V is a skewed ellipse. The more skew the better.
- Shows power is indeed being absorbed by plasma.

# Reversal & Pinch Parameter



- $F$  = reversal parameter
 
$$= \frac{B_{\text{toroidal at wall}}}{\langle B_{\text{toroidal}} \rangle}$$

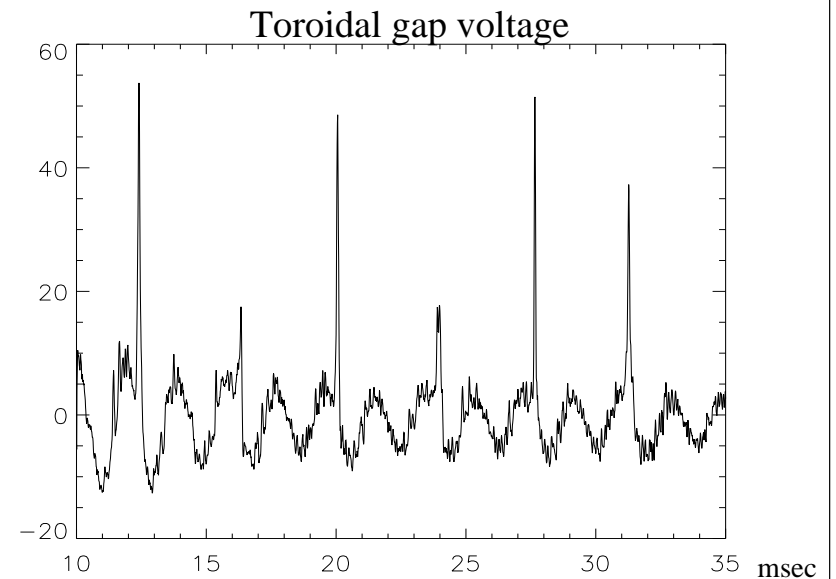
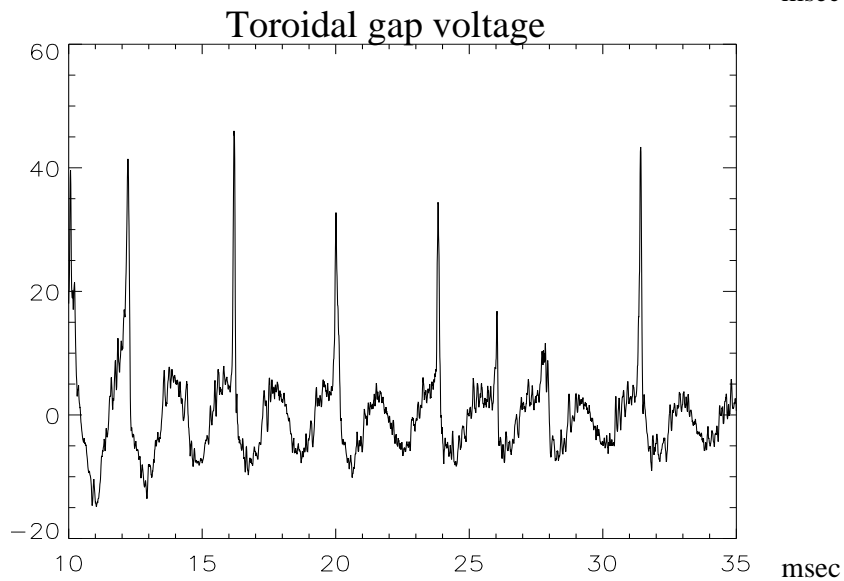
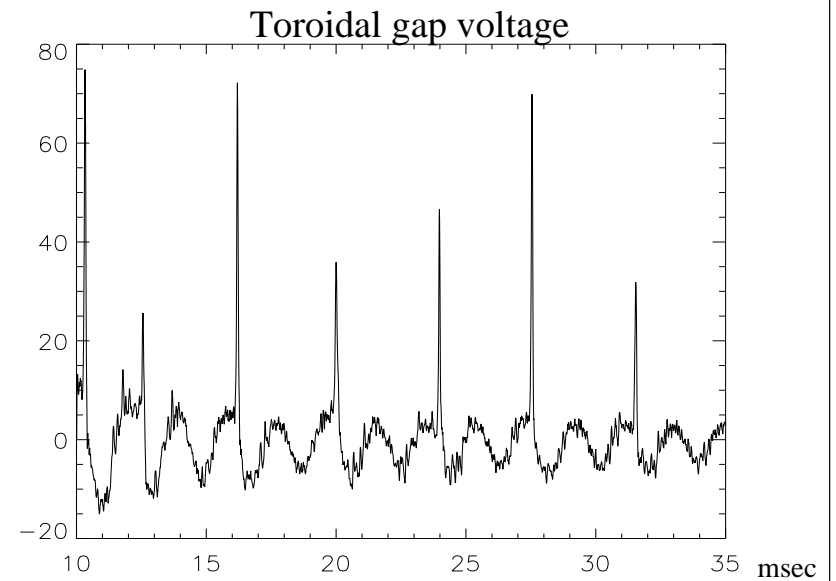
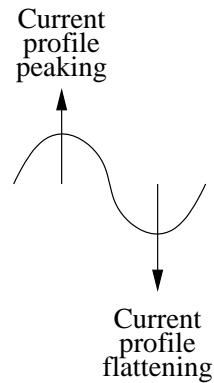
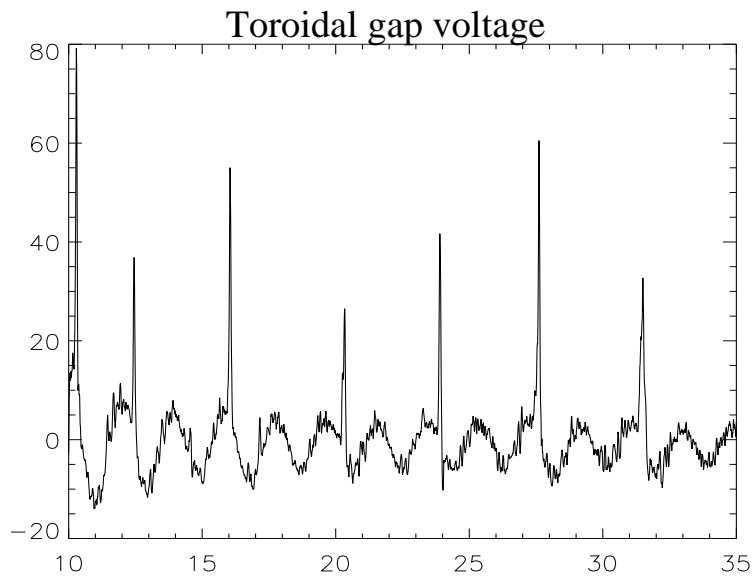
- $\theta$  = pinch parameter
 
$$= \frac{B_{\text{poloidal at wall}}}{\langle B_{\text{toroidal}} \rangle}$$



## Three cycles of $F$ vs $\theta$

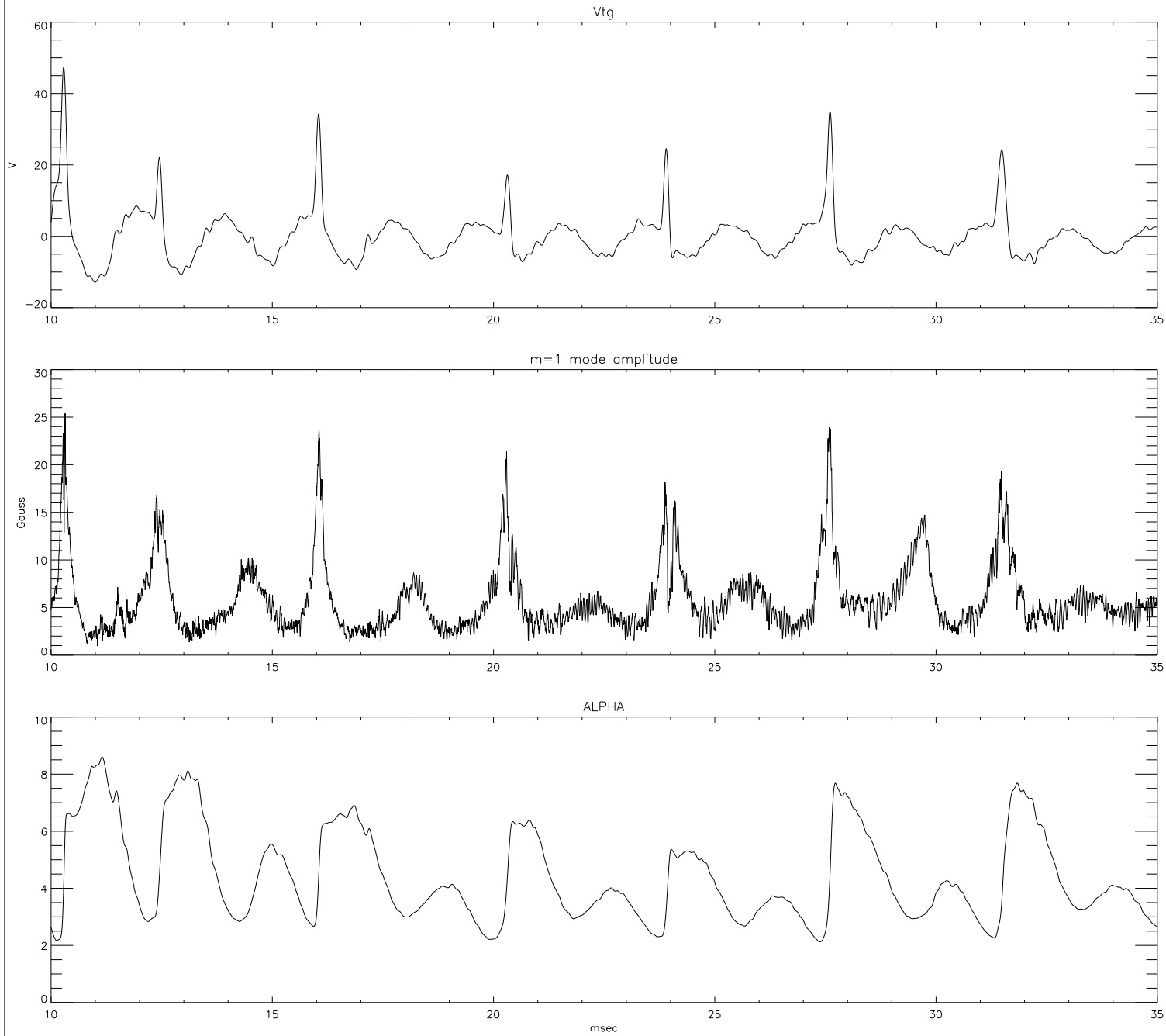
- Two lobes due to sawtooth entrainment
- Trajectory suggests plasma is not relaxed during oscillation cycle.
  - Perhaps lower frequency required

# ROBUST SAWTOOTH ENTRAINMENT

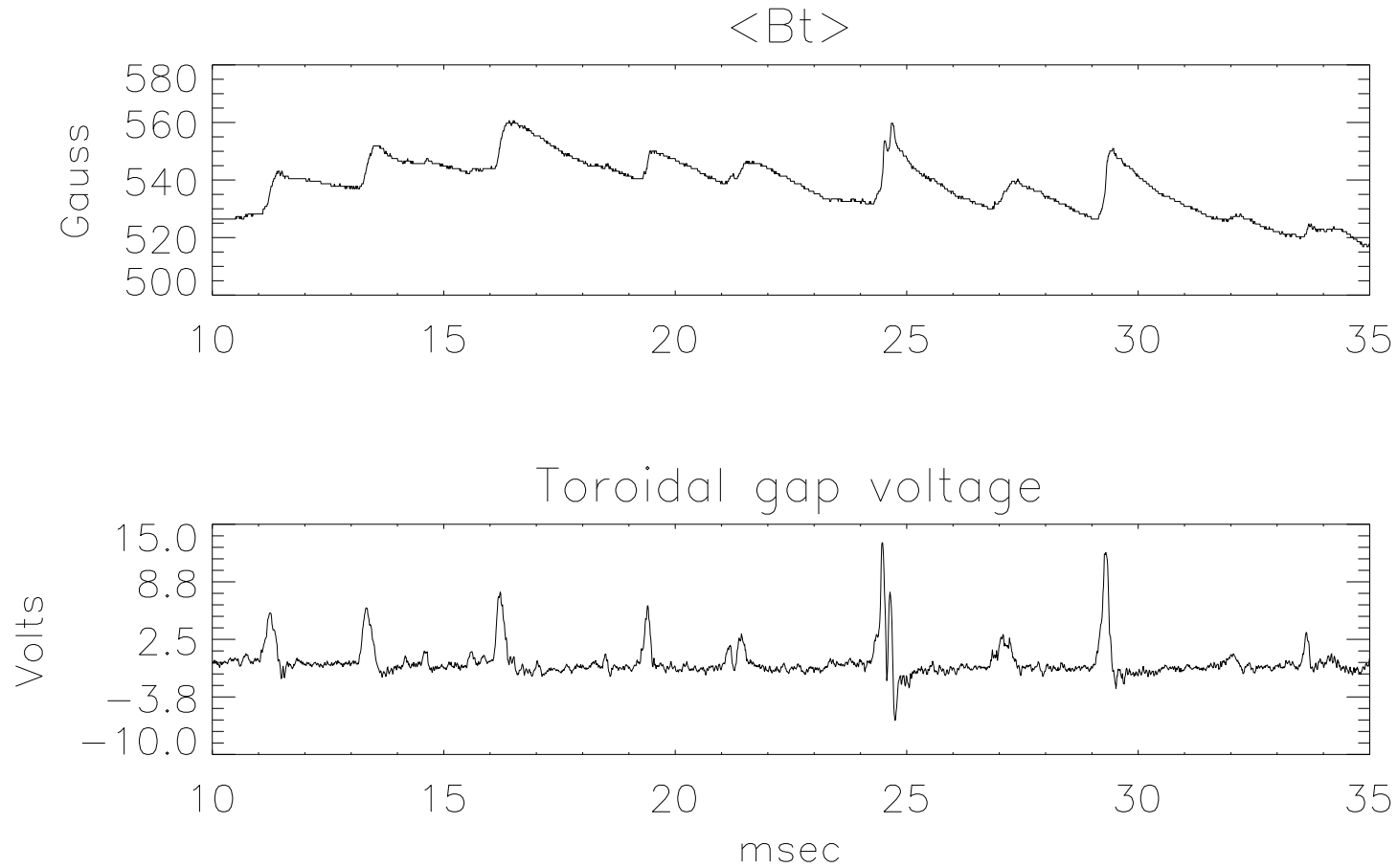


- There is an unmistakable correlation of sawteeth events to oscillations. Event occurs at peak flux injection of every other cycle (anti-PPCD phase)

# FLUCTUATION INCREASE/DECREASE SYNCHRONOUS WITH CURRENT PROFILE PEAKING/FLATTENING

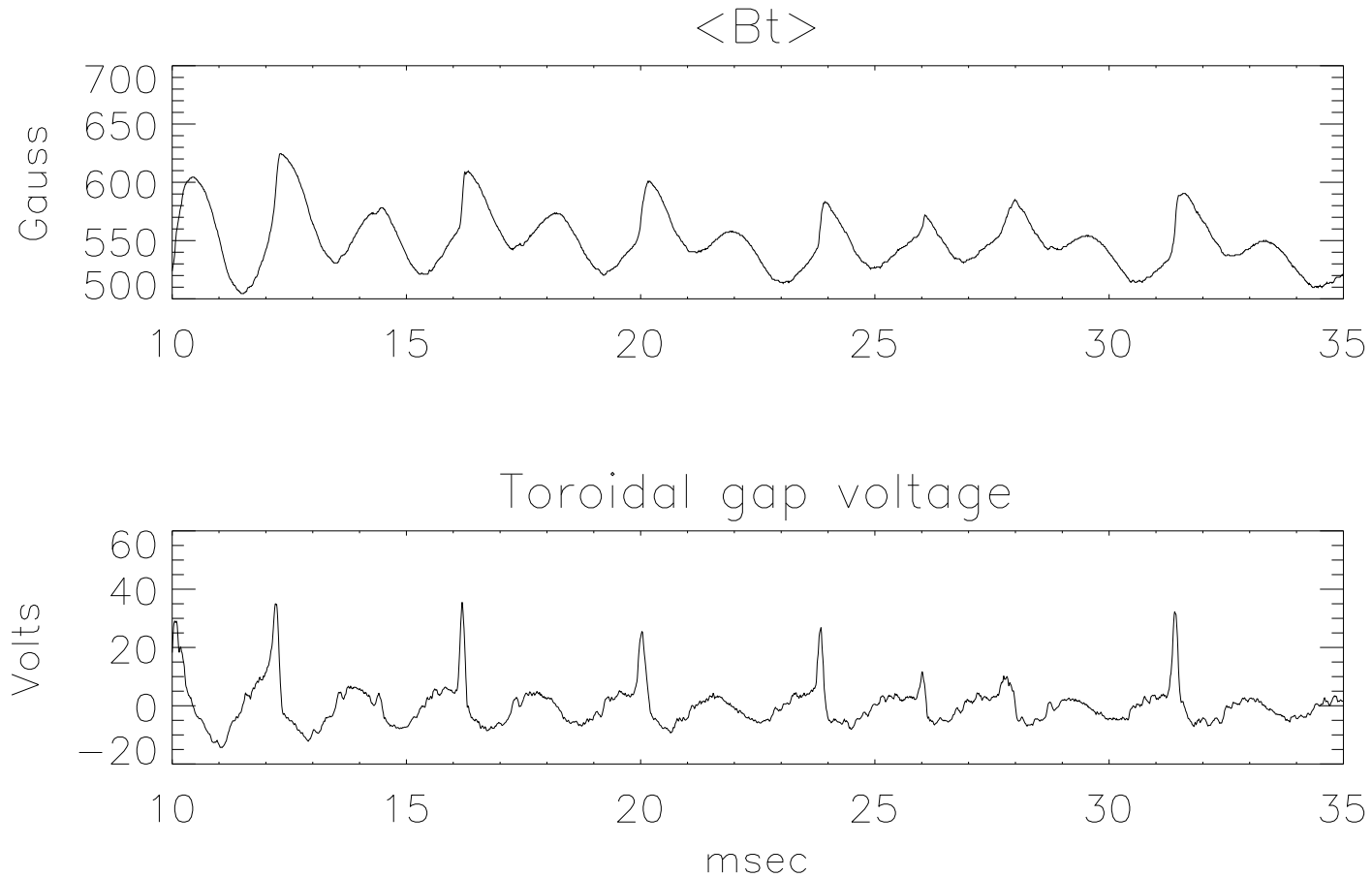


# SAWTEETH OCCUR IRREGULARLY WITHOUT OSCILLATOR



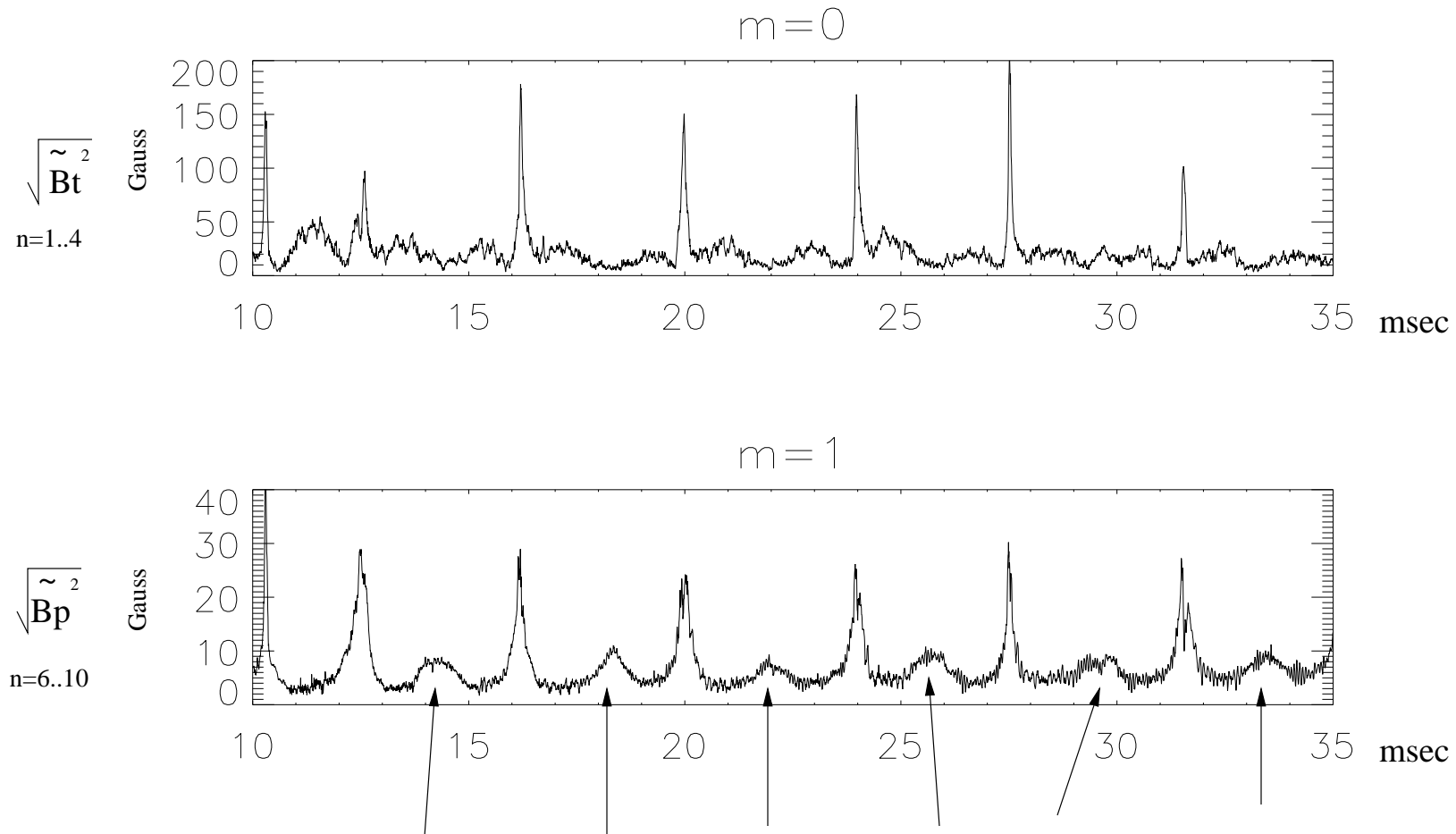
- Typical 250 kA shot. density =  $10^{13}$  per cc

# SAWTEETH ENTRAINED WITH OSCILLATOR



- 250 kA plasma current. density =  $10^{13}$  per cc

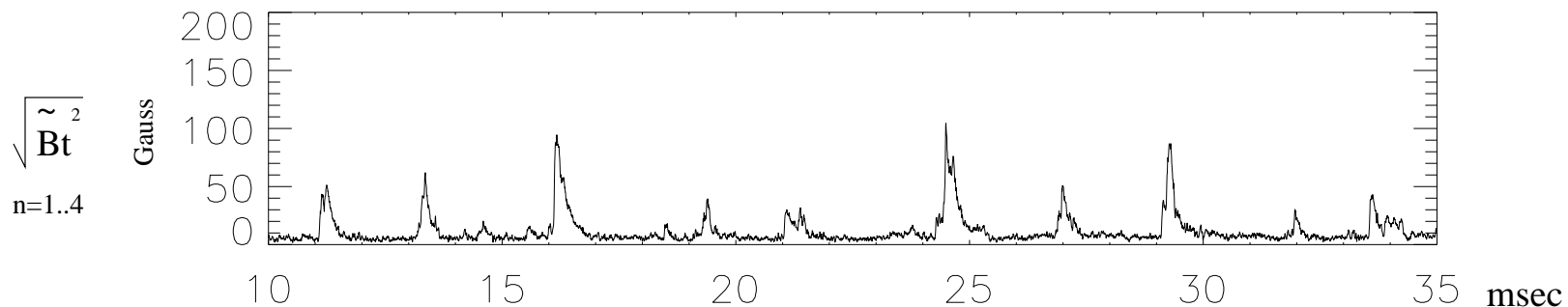
# MODE SPECTRUM WITH OSCILLATOR



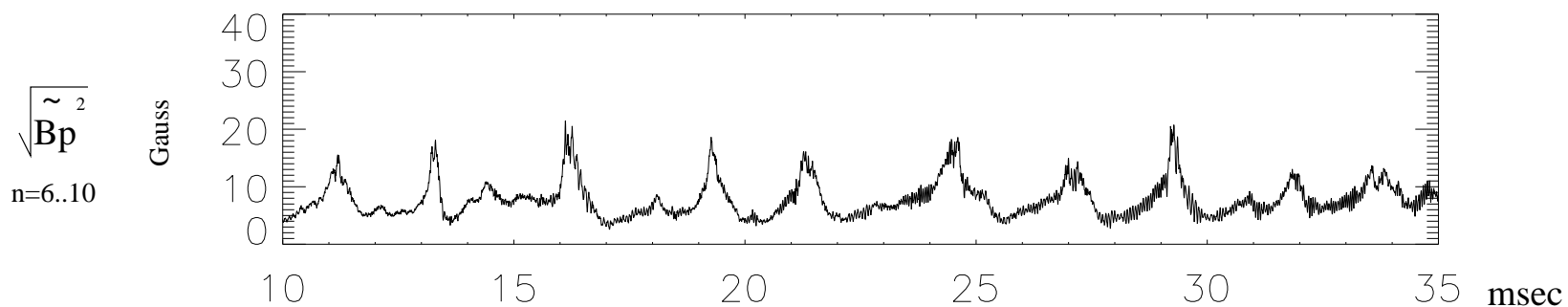
- The increase in  $m=1$  amplitude between sawteeth does not occur in  $m=0$  amplitude.
- Typical 250 kA shot. density =  $10^{13}$  per cc
- Sawteeth are larger, more regularly spaced, and more widely spaced
- $m=0$  average = 20.3 G     $m=1$  average = 7.5 G

# MODE SPECTRUM WITHOUT OSCILLATOR

$m=0$



$m=1$



- For comparison
- $m=0$  average = 12.1 G     $m=1$  average = 8.6 G

# Plans

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- Finish second oscillator
  - Should be done within weeks
  - Begin low power current drive experiments
- Study sawtooth entrainment
  - Vary frequency, plasma current, density
- Replace Ignitrons with Tubes
  - Tubes have faster, more reliable switching performance
  - Tubes used are Machlett model ML8786 tetrodes. 12 MW each
  - Tubes are implemented in a Class-C configuration
    - Looks much like the ignitron based approach
  - Tubes are more expensive than ignitrons (\$80k vs \$10k) but we had them on hand.
  - SPICE Simulations look promising.
  - Good short term high power solution.
- Replace Ignitrons with Solid State Switches
  - Promises performance comparable to tubes
  - Switches are Powerex Gate Commutated Thyristors
    - Oscillator design is for 8 MW.
  - More expensive than ignitrons but less than tubes. \$30k.
  - SPICE Simulations look promising.
  - Probably best long term high power solution

# Summary

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- Built and tested one of two oscillators required for OFCD
  - Oscillator is on toroidal circuit
  - Close to 1 MW peak power
- Observed significant perturbation on toroidal field
  - Some power is absorbed by plasma
- Observed sawtooth entrainment effect
  - Sawteeth occur on flux injection half of every other oscillator cycle, when current profile is peaked.
  - Effect is very consistent
- Lack of  $m=0$  response between sawteeth suggests  $m=0$  mode at sawtooth is linearly unstable rather than nonlinearly driven.