Low power Oscillating Field Current Drive experiments in MST *

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ABSTRACT

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.

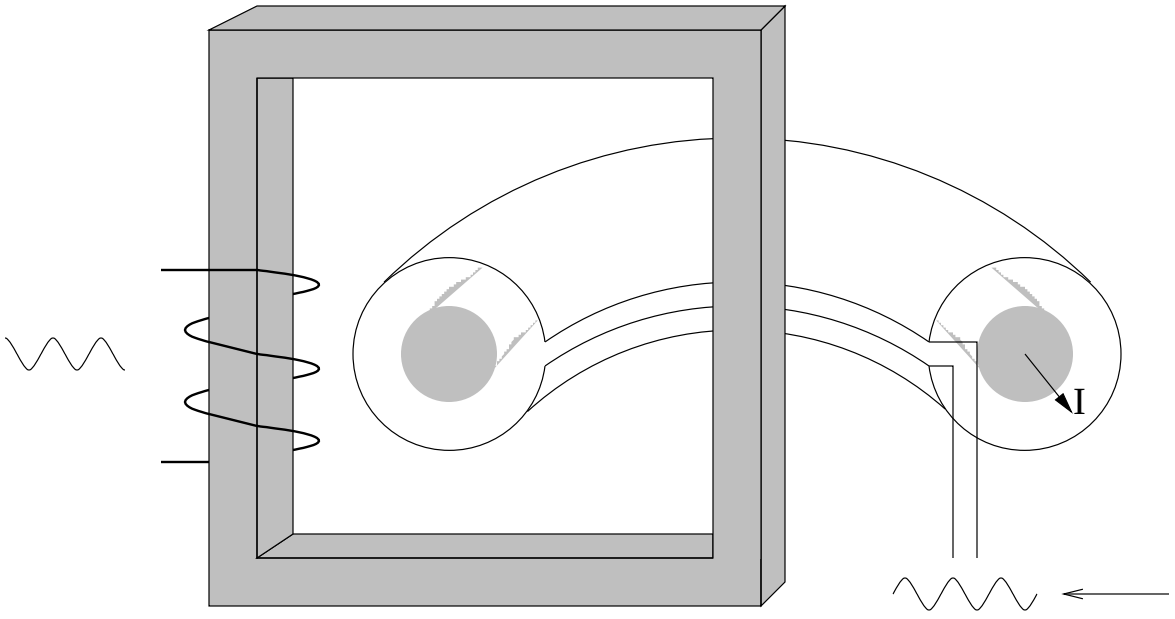
OUTLINE

- 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 (~1MW) 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° out of phase to the poloidal and toroidal circuits.

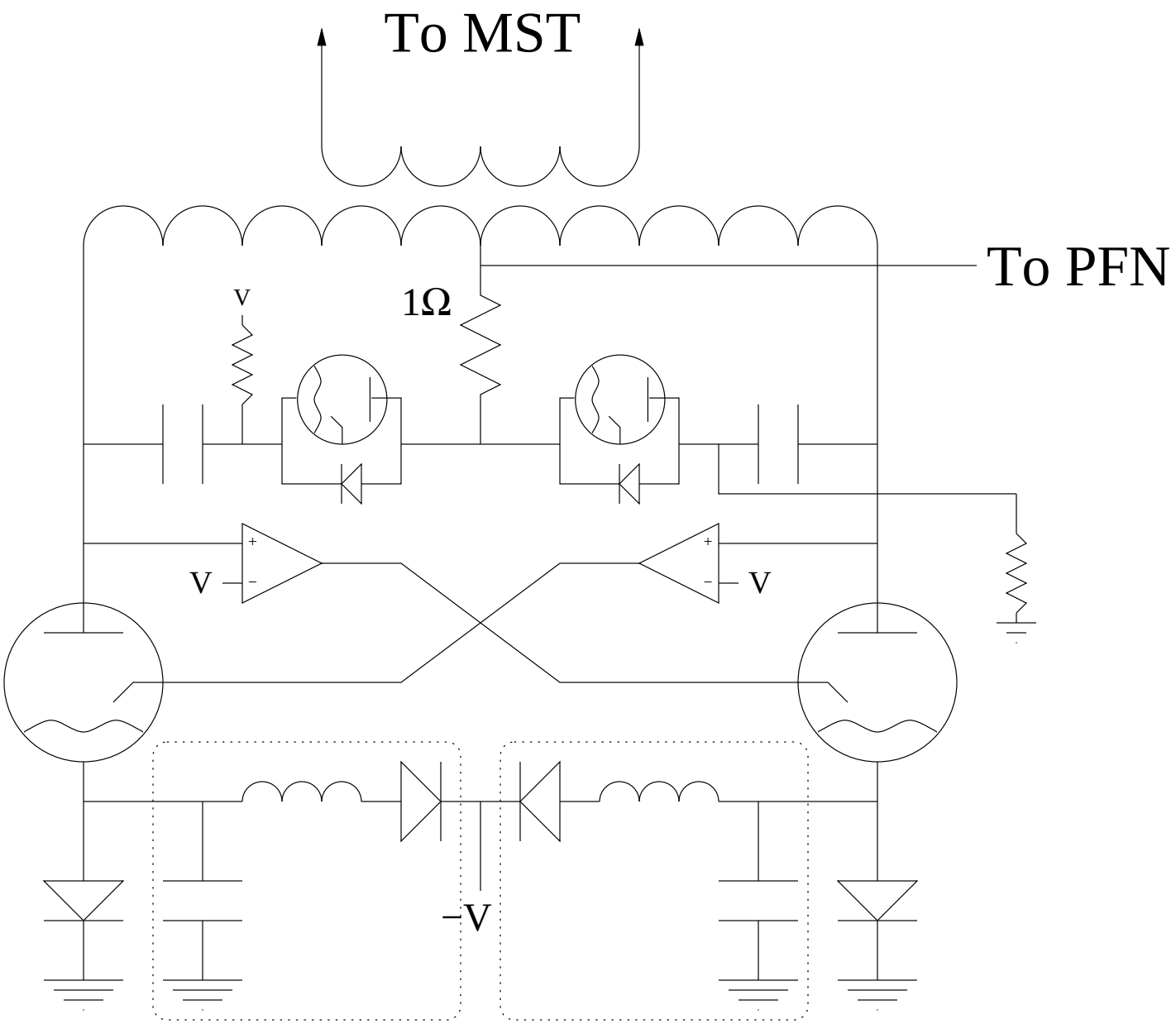


Rectification of oscillating currents is byproduct of conservation of global magnetic helicity.

Frequency for MST plasmas 100−1000 Hz.

Only toroidal oscillator currently implemented

Hybrid Oscillator/Amplifier

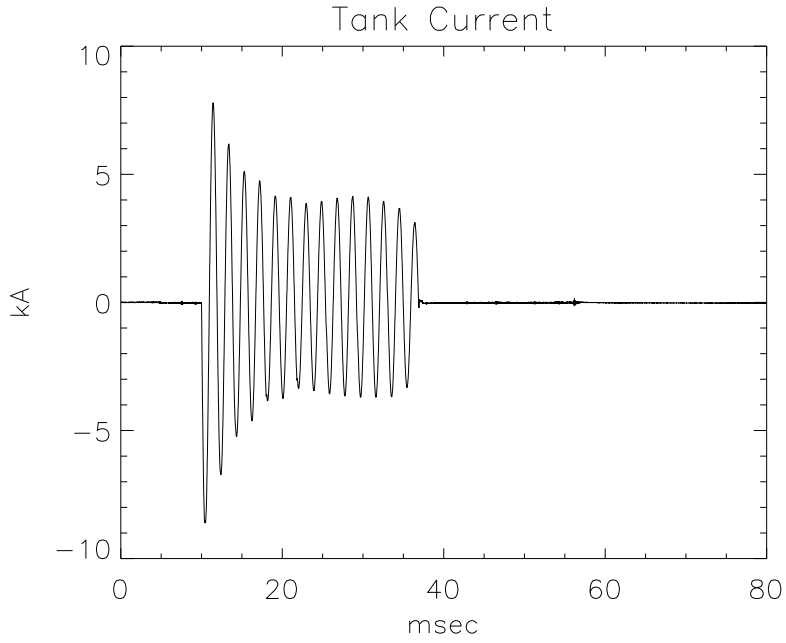


THE EXPERIMENTS

- 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

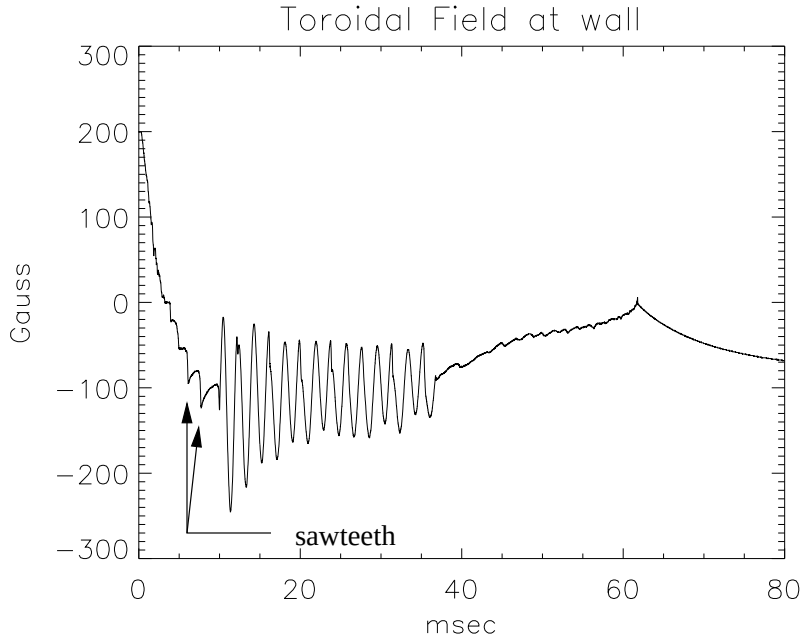
- Circuit variations have included:
  - Splitting the tank circuit
    - Unclear why circuit works better with 1 ohm resistor
  - Paralleling ignitrons for more current
    - No trouble synchronizing ignitors
  - Magnets on the ignitrons
    - Significantly improved turn−off time
  - Tank precharge circuit 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

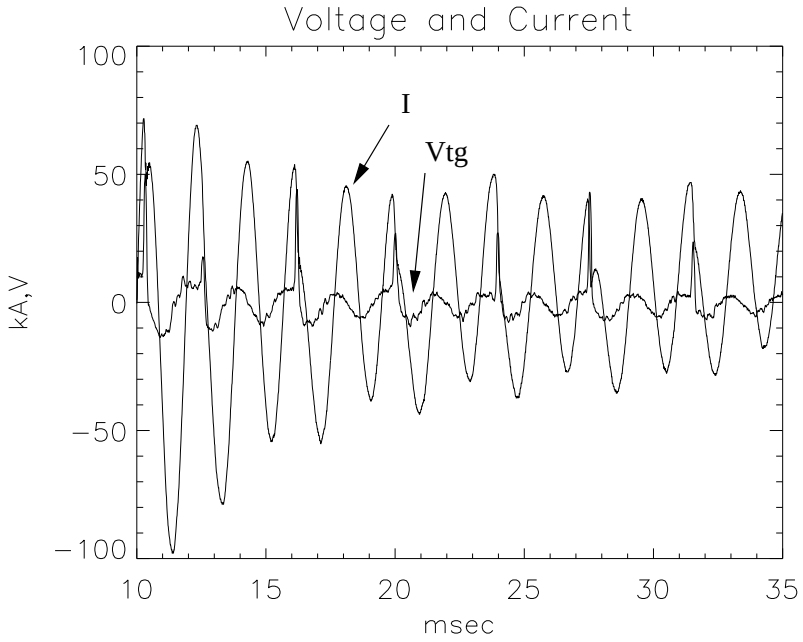
- Shows a well defined pulse. Maximum power achieved on first cycle.
- Pulse width = 14 cycles



Toroidal Field Perturbation

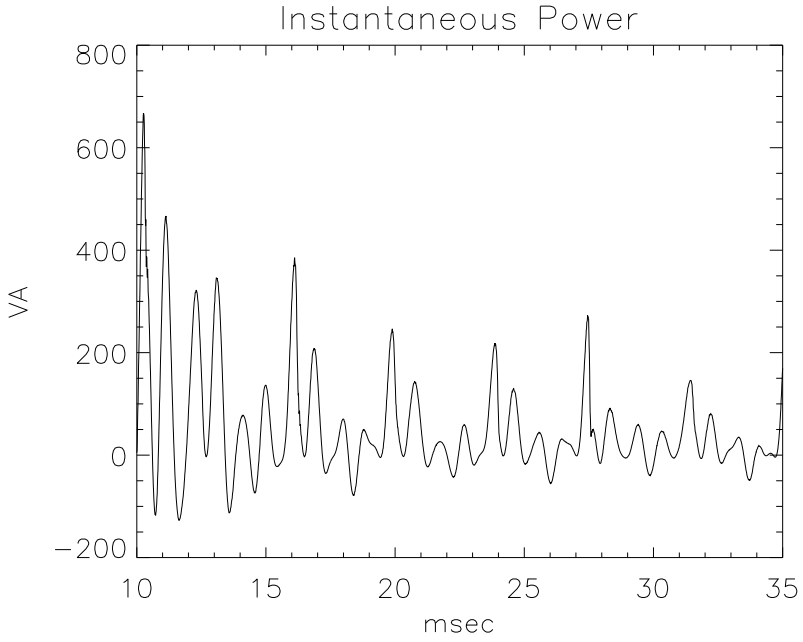
- Oscillation is evident on $B_{toroidal}$ measured at the wall.
- Oscillator is triggered after reversal has occurred.
- Oscillation is significant perturbation compared to sawteeth.

POWER & RESISTIVE LOADING



I and V

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

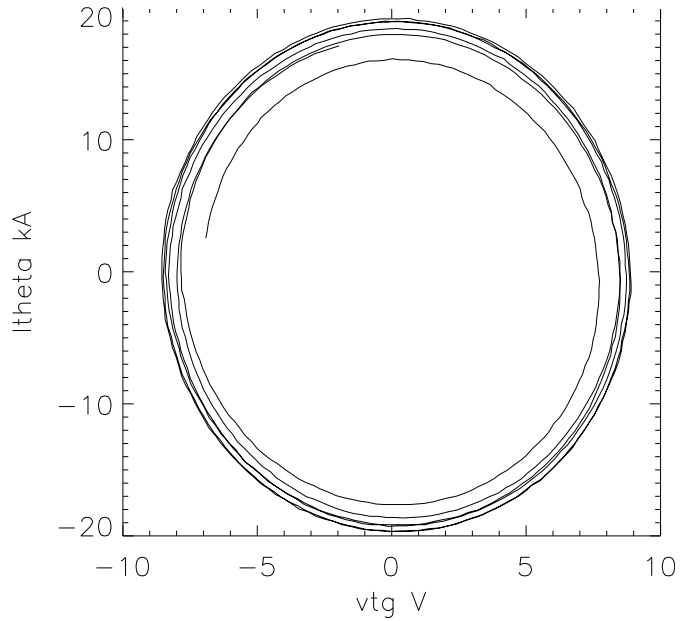


Instantaneous Power

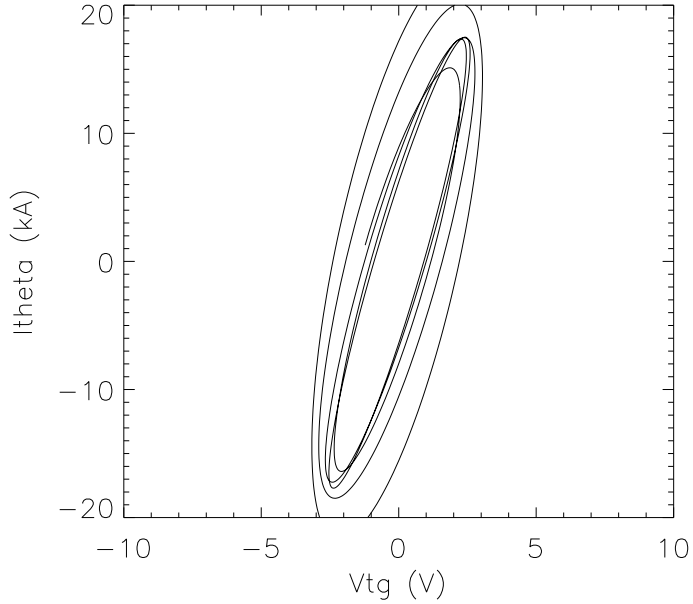
- Shows instantaneous power delivered to plasma.
- Average power = 30 kW
- Peak power = 700 kW

LISSAJOUS PLOTS

I vs V − no plasma

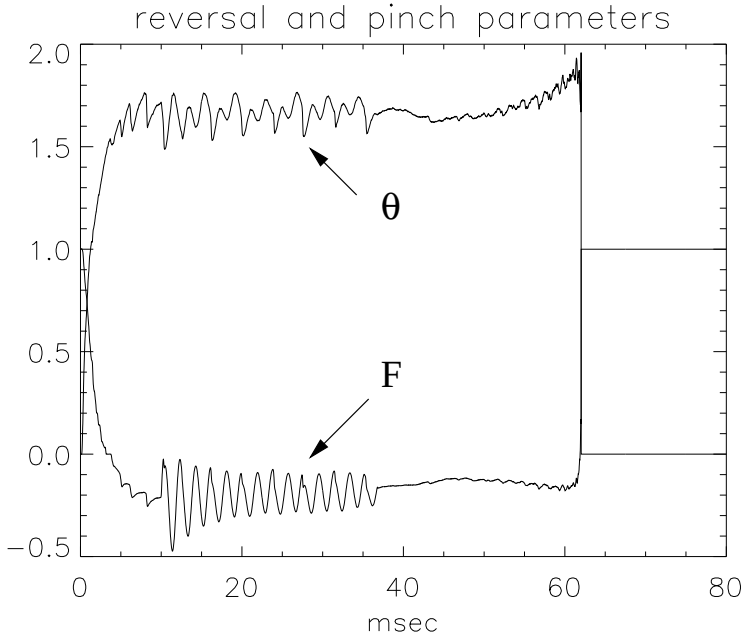


I vs V − with plasma − filtered



- 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.
- Vaccuum 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

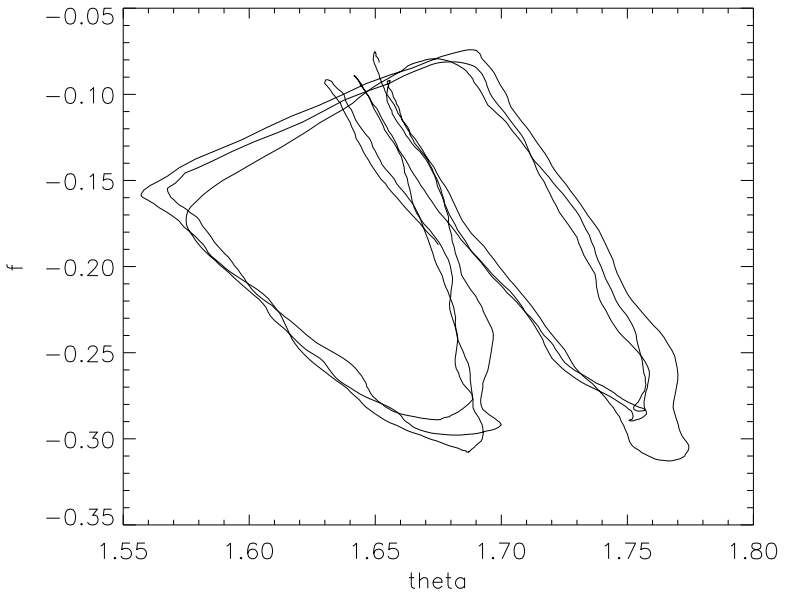


- F=reversal parameter

$$= \frac{B_{\text{toroidal}} \text{ at wall}}{\langle B_{\text{toroidal}} \rangle}$$

- θ = pinch parameter

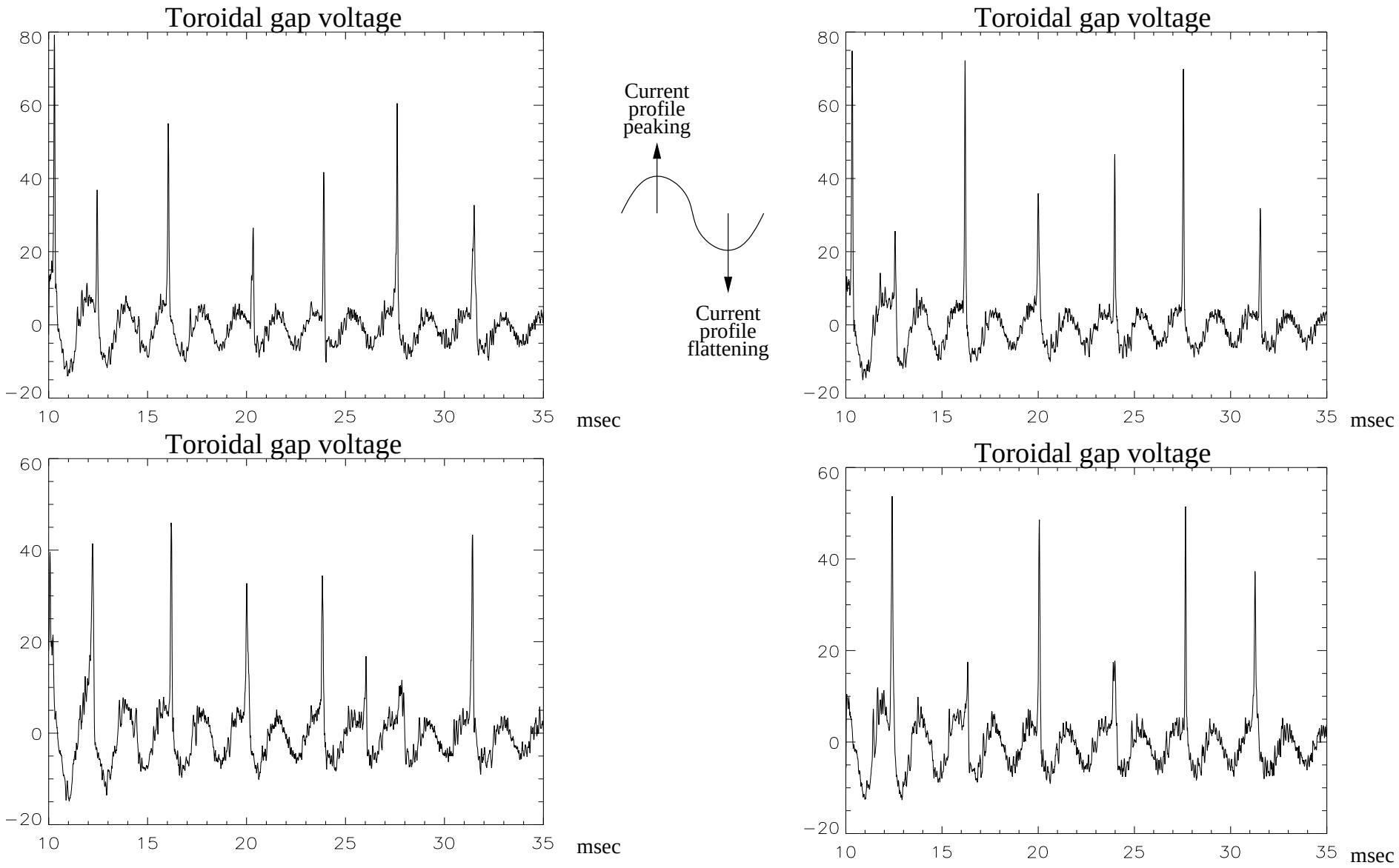
$$= \frac{B_{\text{poloidal}} \text{ at wall}}{\langle B_{\text{toroidal}} \rangle}$$



Three cycles of F vs θ

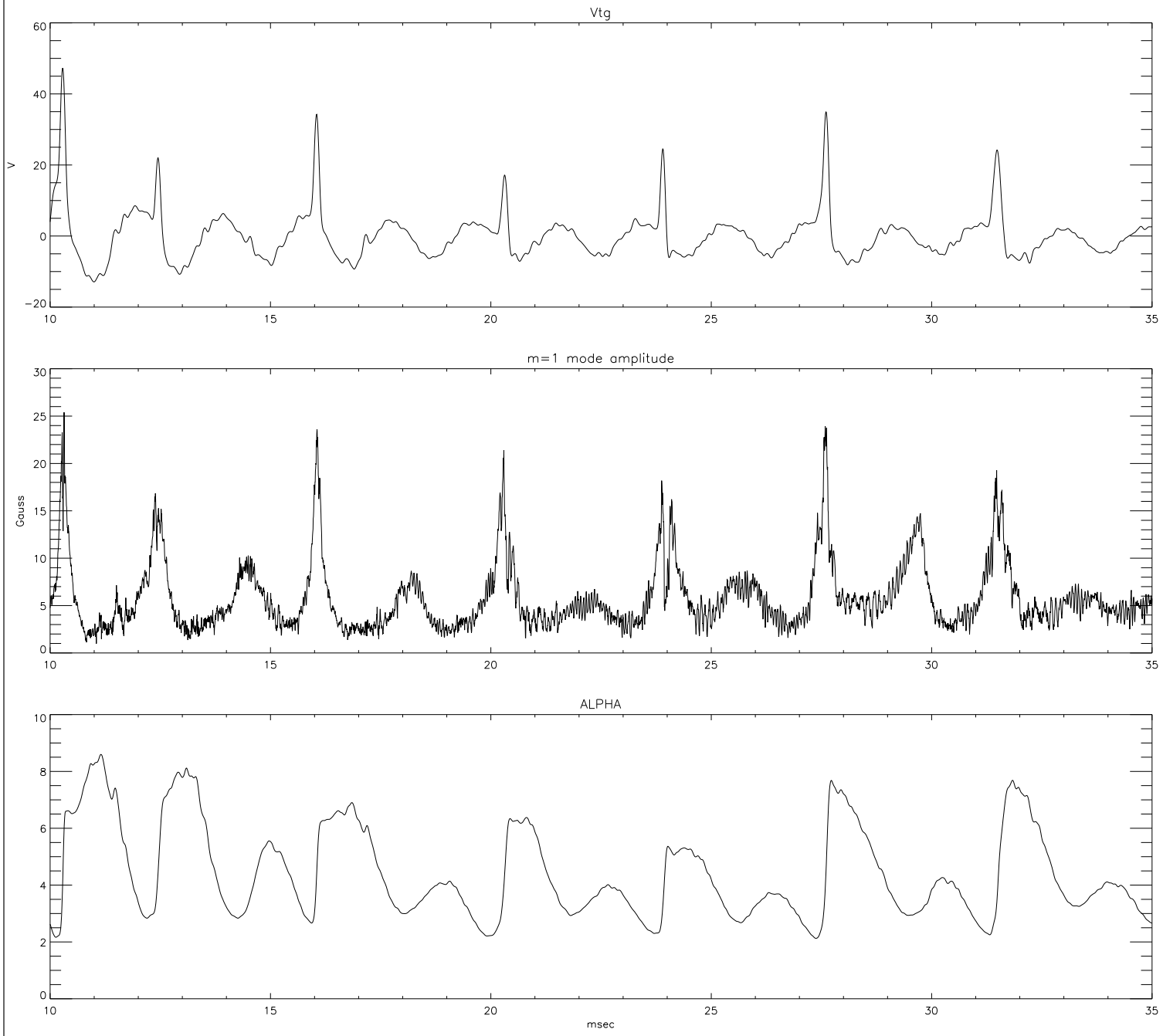
- Two lobes due to sawtooth entrainment
- Trajectory suggests plasma is not relaxed during oscillation cycle.
  — Perhaps lower frequency required

ROBUST SAWTOOTH ENTRAINMENT

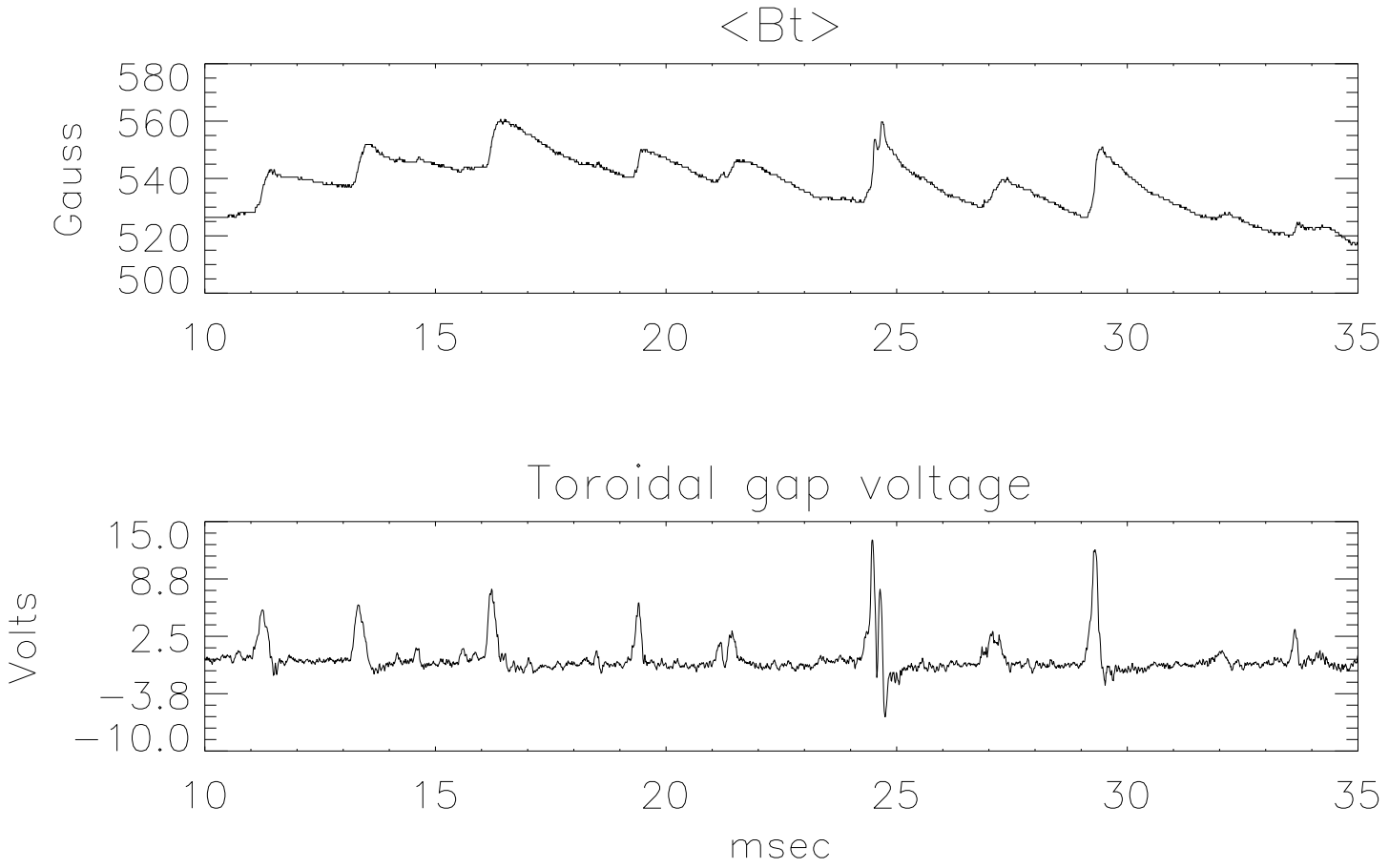


- There is an unmistakable correlation of sawteeth events to oscillations. Event occurs at peak flux injection of every other cycle (anti−PPCD phase)

FLUCTUATION INCREASE/DECREASE SYNCHRONOUS WITH CURRENT PROFILE PEAKING/FLATTENING

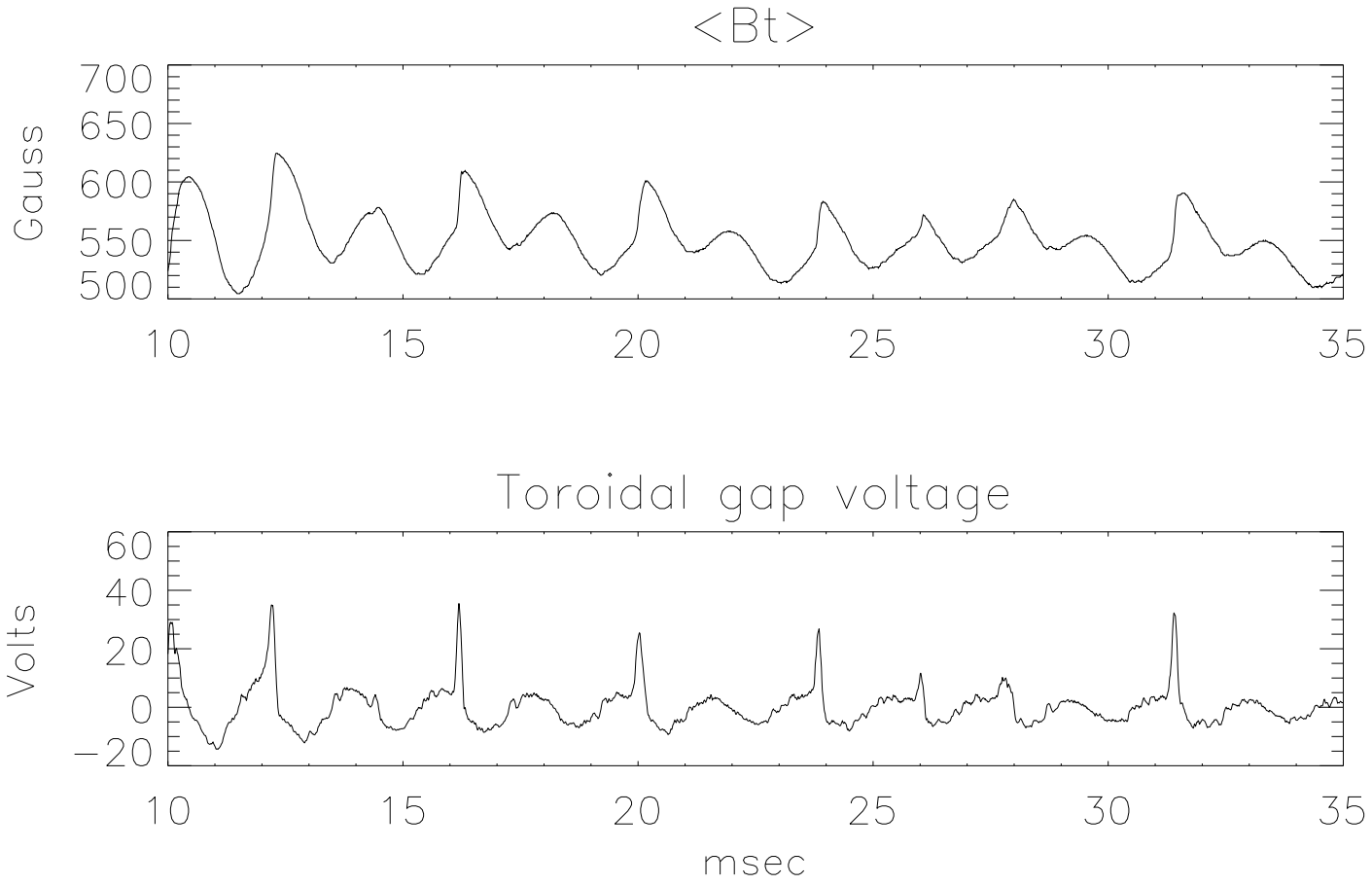


SAWTEETH OCCUR IRREGULARLY WITHOUT OSCILLATOR



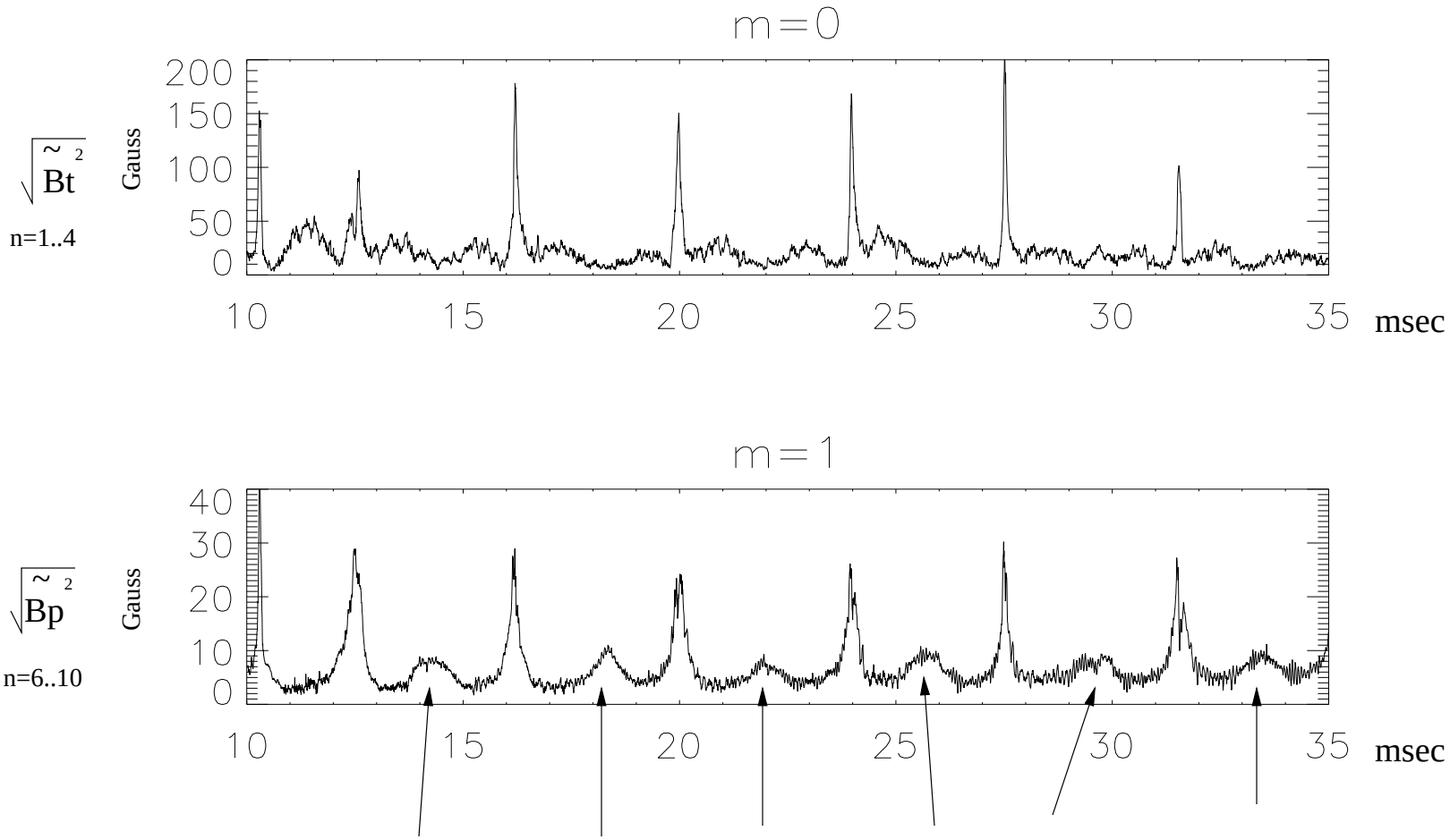
- Typical 250 kA shot. density = 10^{13} per cc

SAWTEETH ENTRAINED WITH OSCILLATOR



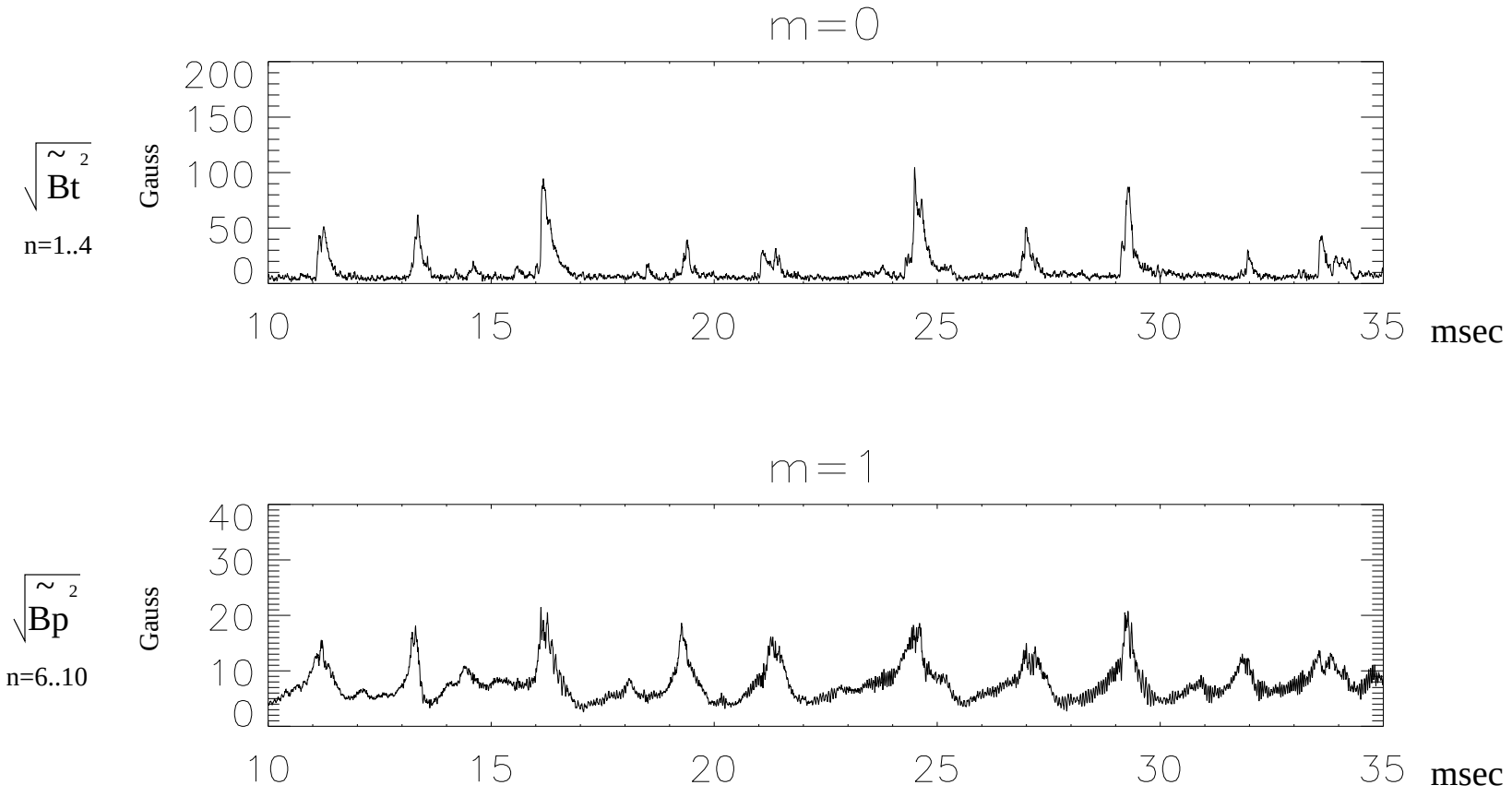
- 250 kA plasma current. density = 10^{13} per cc

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



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

Plans

- 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

- 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.