Observation and Analysis of MHD with the DIII-D Fast MSE System[1]

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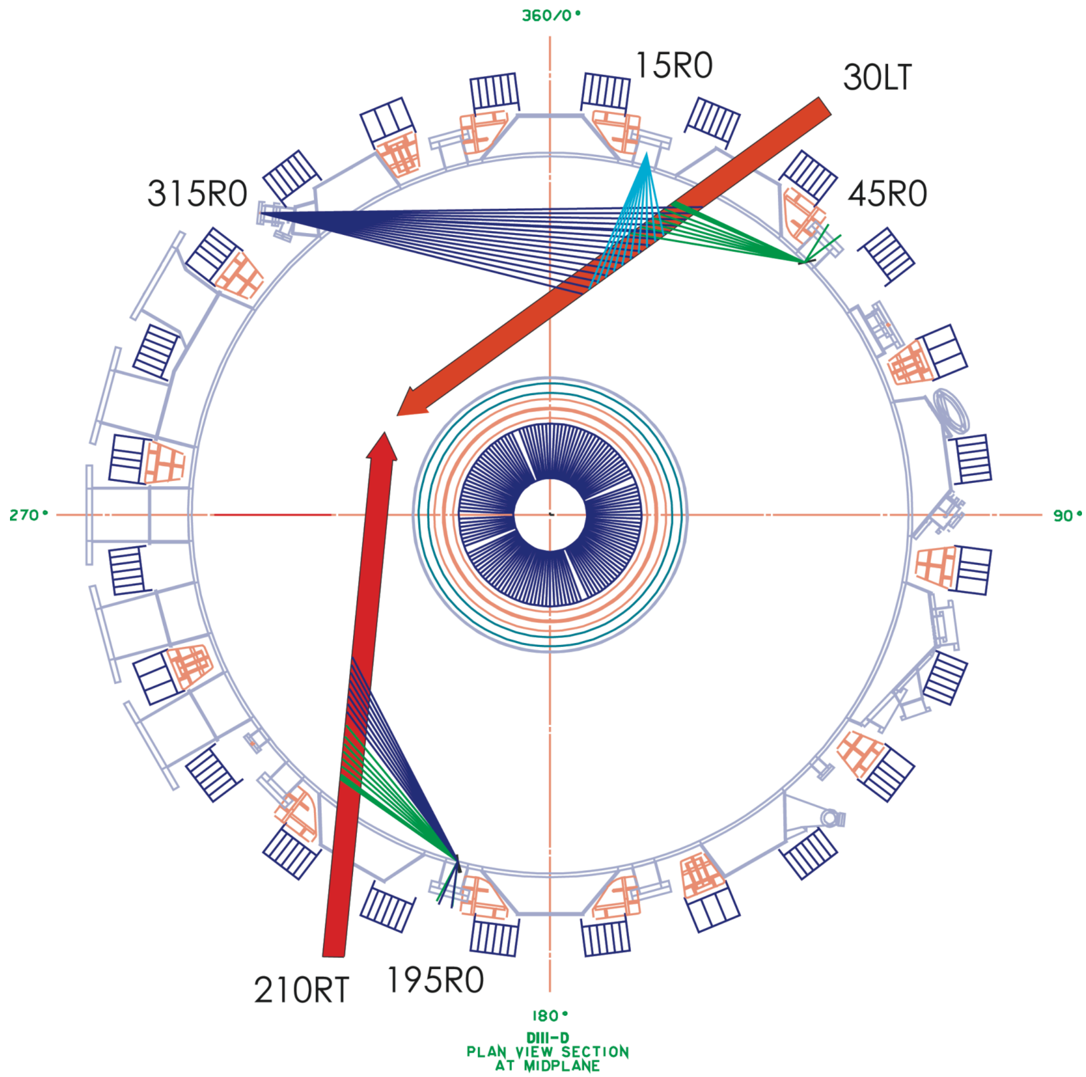
MSE Measures the Local Plasma Pitch Angle

- The Motional Stark Effect (MSE) diagnostic measures the *local* value of the field line pitch angle
- Neutral beam particles experience a Lorentz (v_{beam} x B) electric field causing a Stark shift
- Collisionally excited particles emit linearly polarized light at a wavelength that depends on the beam energy and view angle (Doppler shift)
- The measured polarization is simply related to the local pitch angle by geometric constants
- Standard polarimetry techniques are used to determine the polarization

Two Beam MSE System on DIII-D

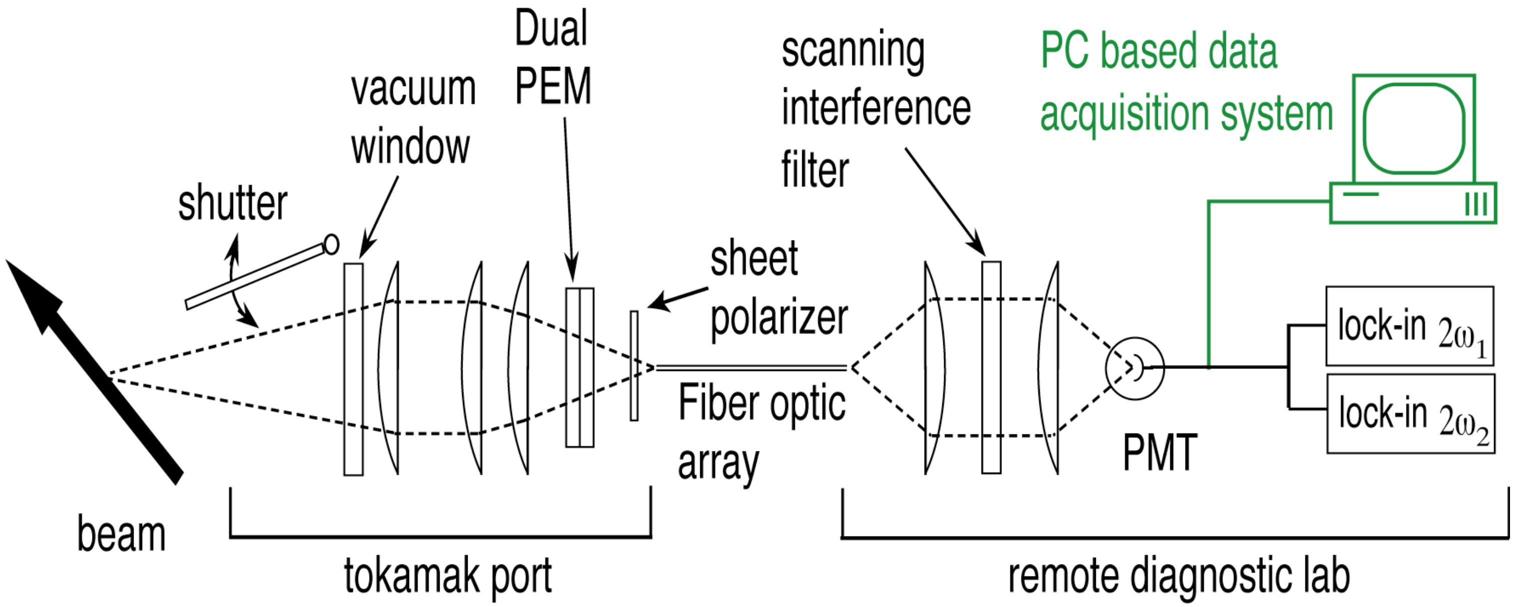


- Currently we have 5 arrays viewing the 30LT and 210RT beams
- An analog system measures the pitch angle on a slow time scale, ~ 1 kHz
- Views of counter propagating neutral beams give maximum sensitivity in the determination of the electric field

MHD Activity has been Observed with the Fast MSE System

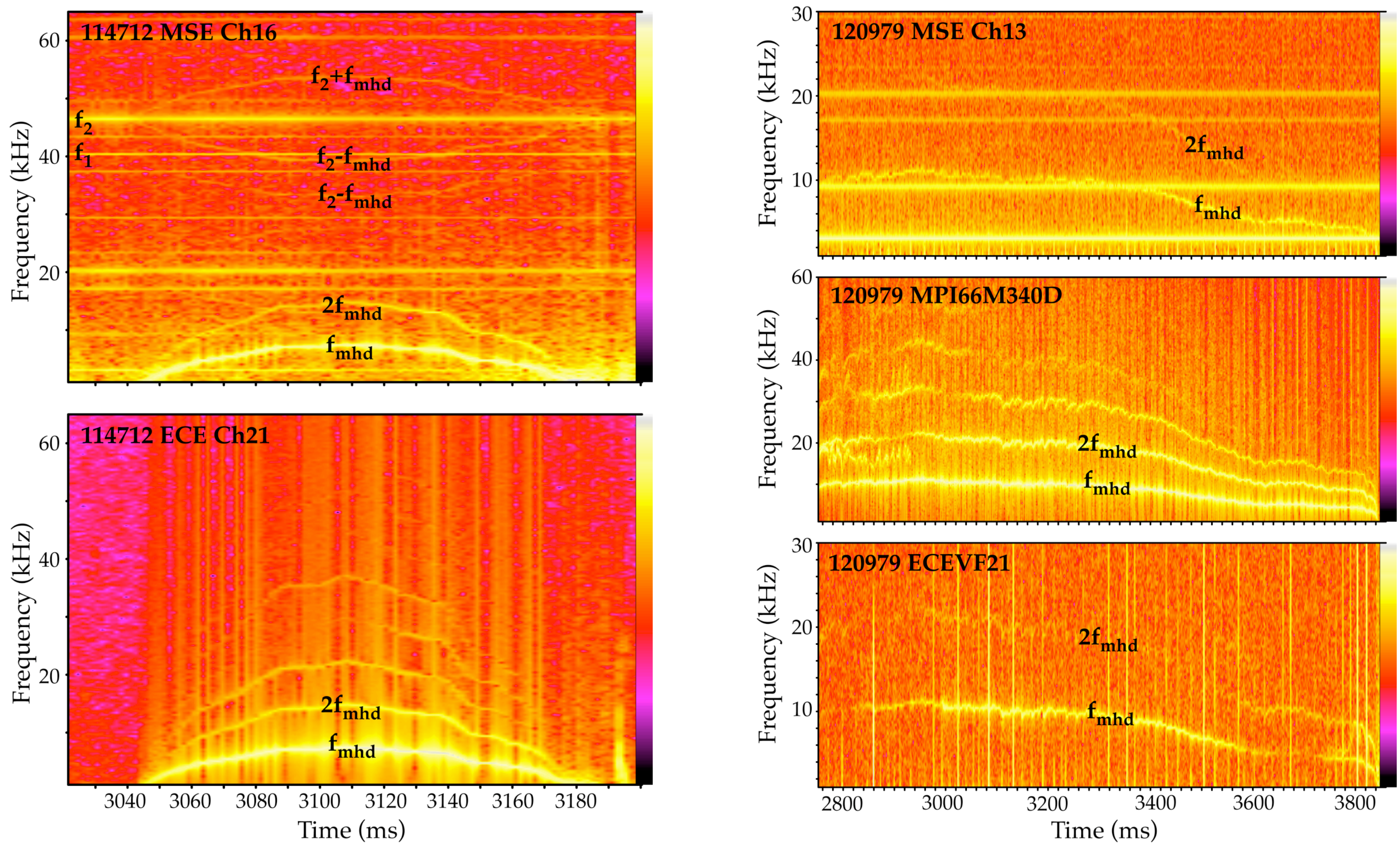
- A prototype PC based digital data acquisition system has been development for the DIII-D MSE diagnostic
- The signals are captured at the output of the PMTs and digitized at rates up 1 MHz with 12 bit resolution
- MHD phenomena have been observed on the fast system and a method has been developed to interpret the signals
- The analysis tools that have been developed can be applied to a wider range of problems

Prototype Fast MSE System has a Flexible Configuration



- Fast MSE system acquires a maximum of 12 channels
- Acquired channels can be selected from any of the 36 channels comprising the 315° and 45° arrays
- Data is stored in a local MDSPlus server

Spectrum of Fast MSE Signal Shows the Same MHD Signal as other Diagnostics



Interpretation of the Signal is Complicated by Associated Density Fluctuations

- Signatures of MHD activity that are well correlated with other diagnostics are observed on fast MSE data
- Such observations are indicative of *local pitch angle fluctuations* due to the presence of the MHD mode
- Interpretation of the raw signal is complicated as it depends on the total intensity (proportional to $n_e n_{beam}$)
- Therefore, the observed fluctuation is dependent on changes in both the density and pitch angle.
- In a quiescent discharge, the ratio of two signals is used to remove the density dependence and derive the static (equilibrium) pitch angle
- A more elaborate analysis technique is needed to determine the contribution due to the pitch angle fluctuation alone

Mueller Matrix Model Forms Basis of Analysis

- The optical system is modeled by a cascade of Mueller matrices which operate on the Stokes vector corresponding to the polarization of the incident light
- Perturbations are taken as

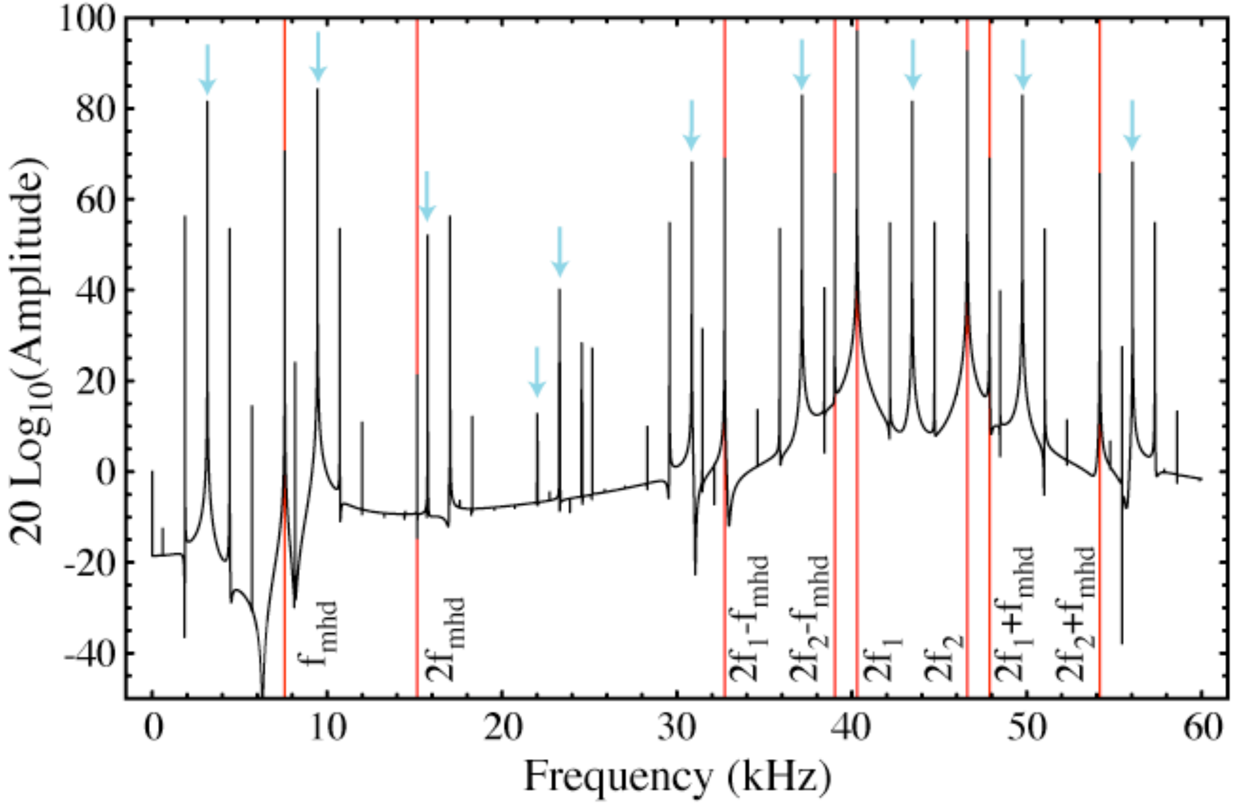
$$\gamma + \tilde{\gamma}\cos(\omega_{mhd} t + \varphi_g)$$

$$n_0[1 + \tilde{n}\cos(\omega_{mhd} t + \varphi_n)]$$

- Photoelastic modulators (PEMs) in the optical system modulate the polarization of the incident light and mix non-linearly with the MHD oscillation to produce a complex spectrum
- The primary challenge in the analysis is to simultaneously determine the phase and amplitude of the density and pitch angle contributions

Spectrum of Mixed MSE and MHD Signals is Rich

Simulated MSE Spectrum

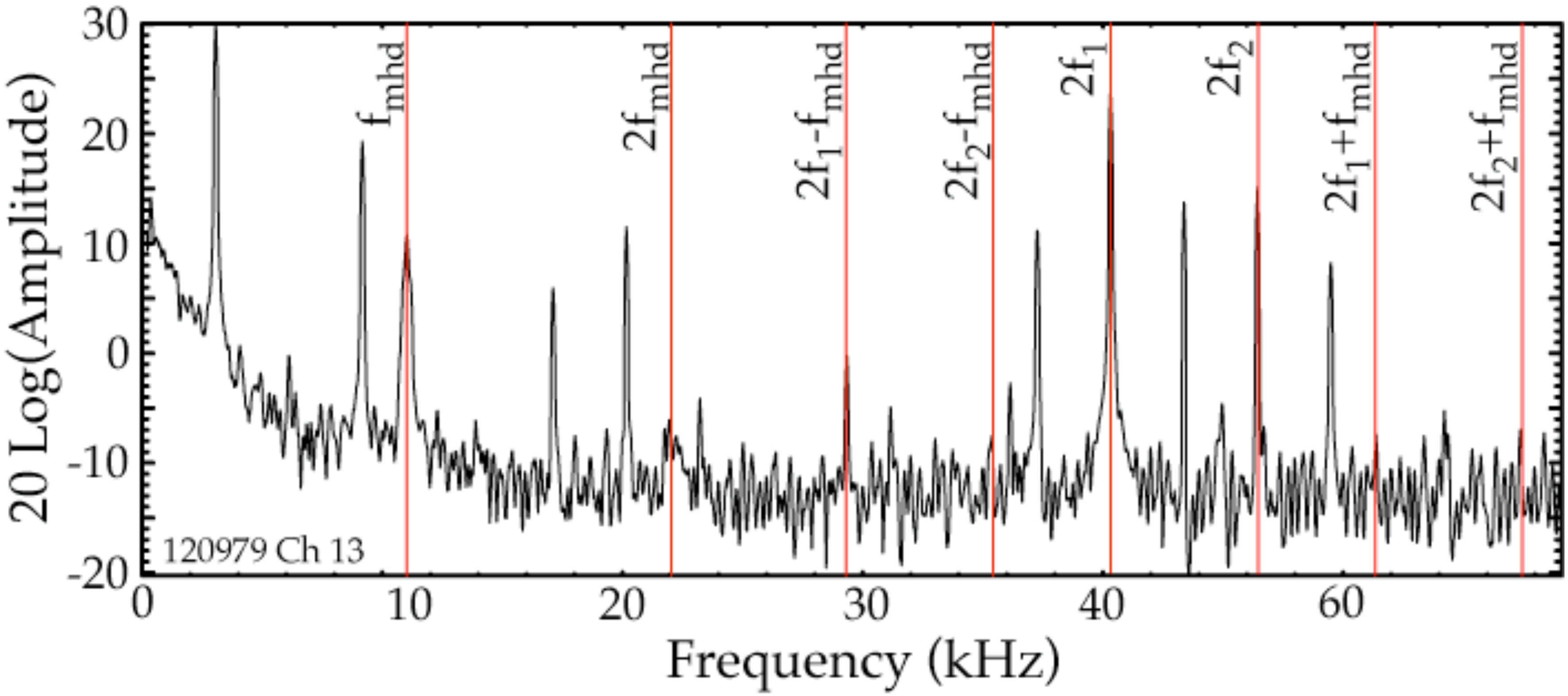


- Blue arrows indicate peaks present in an MHD-free case
- Red lines indicate frequencies normally observed when MHD is present

- f_1 and f_2 are the (fundamental) PEM modulation frequencies
- f_{mhd} is the frequency of the MHD oscillation

Model Explains All Observed Peaks in the Spectrum

- The measured phases and amplitudes of various spectral peaks of the FFT can be related to the phase and amplitude of the density and pitch angle perturbations



Fluctuation Parameters are Encoded in the Amplitude and Phase of the Main Spectral Peaks

ω	Amplitude	Phase
ω_{mhd}	$\frac{1}{4}(I_\pi + I_\sigma)\left\{\tilde{n}^2\left[1 - PJ_0(A_{12})\cos 2\gamma\right] + 4\tilde{\gamma}^2 P^2 J_0^2(A_{12})\sin^2 2\gamma + 4P\tilde{\gamma}\tilde{n}J_0(A_{12})\sin 2\gamma\left[1 - PJ_0(A_{12})\cos 2\gamma\right]\cos(\varphi_g - \varphi_n)\right\}^{1/2}$	$\tan^{-1}\left[\frac{\left[1 - PJ_0(A_{12})\cos 2\gamma\right]\sin\varphi_n + rPJ_0(A_{12})\sin 2\gamma \sin\varphi_g}{\left[1 - PJ_0(A_{12})\cos 2\gamma\right]\cos\varphi_n + rPJ_0(A_{12})\sin 2\gamma \cos\varphi_g}\right]$
$2\omega_1$	$\frac{1}{\sqrt{2}}(I_\pi - I_\sigma)J_2(A_1)\cos 2\gamma_1$	$2\varphi_1$
$2\omega_1 + \omega_{mhd}$	$\frac{1}{2\sqrt{2}}(I_\pi - I_\sigma)J_2(A_1)\{\tilde{n}^2\cos^2 2\gamma_1 + 4\tilde{\gamma}^2\sin^2 2\gamma_1 - 4\tilde{n}\tilde{\gamma}\cos 2\gamma_1 \sin 2\gamma_1 \cos(\varphi_g - \varphi_n)\}^{1/2}$	$\tan^{-1}\left[\frac{\sin(\varphi_n + 2\varphi_1) - r\tan 2\gamma_1 \sin(\varphi_g + 2\varphi_1)}{\cos(\varphi_n + 2\varphi_1) - r\tan 2\gamma_1 \cos(\varphi_g + 2\varphi_1)}\right]$
$2\omega_1 - \omega_{mhd}$	$\frac{1}{2\sqrt{2}}(I_\pi - I_\sigma)J_2(A_1)\{\tilde{n}^2\cos^2 2\gamma_1 + 4\tilde{\gamma}^2\sin^2 2\gamma_1 - 4\tilde{n}\tilde{\gamma}\cos 2\gamma_1 \sin 2\gamma_1 \cos(\varphi_g - \varphi_n)\}^{1/2}$	$-\tan^{-1}\left[\frac{\sin(\varphi_n - 2\varphi_1) - r\tan 2\gamma_1 \sin(\varphi_g - 2\varphi_1)}{\cos(\varphi_n - 2\varphi_1) - r\tan 2\gamma_1 \cos(\varphi_g - 2\varphi_1)}\right]$
$2\omega_2$	$\frac{1}{\sqrt{2}}(I_\pi - I_\sigma)J_2(A_2)\sin 2\gamma_1$	$2\varphi_2$
$2\omega_2 + \omega_{mhd}$	$\frac{1}{2\sqrt{2}}(I_\pi - I_\sigma)J_2(A_2)\{\tilde{n}^2\sin^2 2\gamma_1 + 4\tilde{\gamma}^2\cos^2 2\gamma_1 + 4\tilde{\gamma}\tilde{n}\cos 2\gamma_1 \sin 2\gamma_1 \cos(\varphi_g - \varphi_n)\}^{1/2}$	$\tan^{-1}\left[\frac{\sin(\varphi_n + 2\varphi_2)\tan 2\gamma_1 + r\sin(\varphi_g + 2\varphi_2)}{\cos(\varphi_n + 2\varphi_2)\tan 2\gamma_1 + r\cos(\varphi_g + 2\varphi_2)}\right]$
$2\omega_2 - \omega_{mhd}$	$\frac{1}{2\sqrt{2}}(I_\pi - I_\sigma)J_2(A_2)\{\tilde{n}^2\sin^2 2\gamma_1 + 4\tilde{\gamma}^2\cos^2 2\gamma_1 + 4\tilde{\gamma}\tilde{n}\cos 2\gamma_1 \sin 2\gamma_1 \cos(\varphi_g - \varphi_n)\}^{1/2}$	$-\tan^{-1}\left[\frac{\sin(\varphi_n - 2\varphi_2)\tan 2\gamma_1 + r\sin(\varphi_g - 2\varphi_2)}{\cos(\varphi_n - 2\varphi_2)\tan 2\gamma_1 + r\cos(\varphi_g - 2\varphi_2)}\right]$

Definitions

I_π, I_σ = Intensity of the π and σ lines

$P = \frac{I_\pi - I_\sigma}{I_\pi + I_\sigma}$ = Polarization ratio

J_0, J_2 = Bessel functions of first kind of order 0 and 2

A_1, A_2 = Amplitudes of the PEM modulation

A_{12} = Common PEM modulation amplitude (assumes $A_1 = A_2$)

$r = 2\tilde{\gamma}/\tilde{n}$ = ratio of fluctuation amplitudes

$\tilde{\gamma}, \tilde{n}$ = pitch angle and density perturbation amplitudes

φ_g, φ_n = phases of the pitch angle and density pertubations

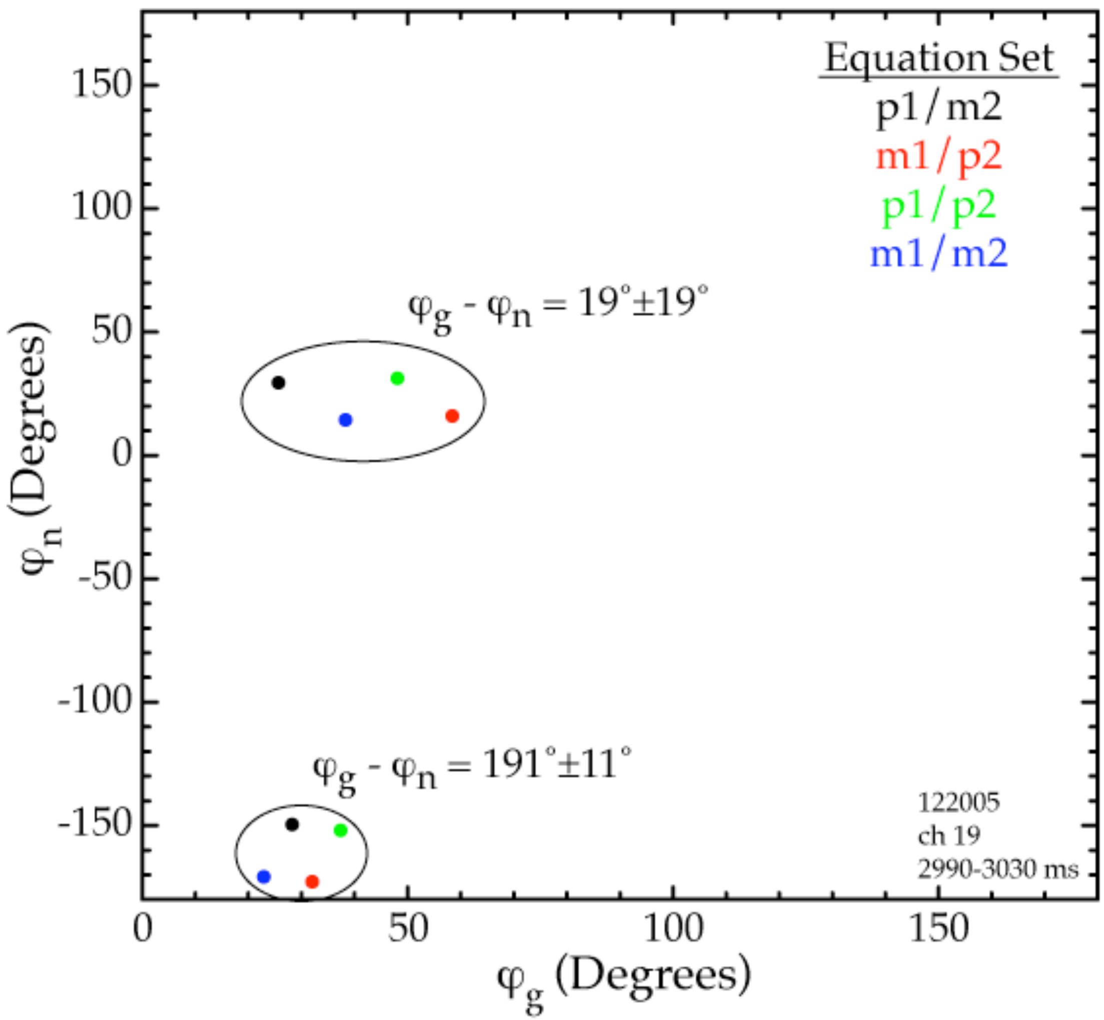
φ_1, φ_2 = phases of the PEM modulations

$\gamma = \gamma_1 - \pi/8$ = magnetic pitch angle at the measurement location

There is Sufficient Information in the Spectrum to Solve for the Unknown Parameters

- Main peaks are at $2f_1 \pm f_{mhd}$ and $2f_2 \pm f_{mhd}$ with amplitude and phase information at each
- The f_{mhd} peak cannot be used in the initial solution because it contains an additional unknown, P, the polarization fraction
- Relating the measured phases and ratios of amplitudes to the expressions in the table leads to multiple sets of coupled transcendental equations for the unknown phases (φ_g, φ_n) and perturbation amplitudes ($\tilde{n}$ and $\tilde{\gamma}$)
- Solutions to these equations can be found relatively easily
- Moreover, solutions from different equation sets are consistent with one another
- The f_{mhd} peak may then be used to determine P, a quantity that we cannot otherwise measure experimentally

Multiple Roots are Often Found



- Relative phase between the density and pitch angle fluctuation (φ_g - φ_n) is the quantity of physical interest
- Since the equations are transcendental, multiple roots are often found
- Have yet to find a way to distinguish the roots physically

Inferred Quantities

- Solution yields the following quantities

$$\tilde{\gamma} = 0.024 \qquad \tilde{B}_z = 360\,\mathrm{G}$$
$$\tilde{n} = 0.15 \qquad I_s / I_p = 1.9$$

- Mode amplitude is very large, $\tilde{B}_z \sim 10\mathrm{x}$ magnetic probe value
- Attribute this to non-ideal effects not initially modeled due to retardance in a mirror in the optical train of the edge channels
- When a correction is applied for the mirror retardance the following solution is obtained:

$$\tilde{\gamma}_{\min} = 0.0008 \qquad \tilde{B}_{z,\min} = 12\,\mathrm{G} \qquad \varphi_g - \varphi_n = \begin{cases} 9^\circ \pm 9^\circ \\ 201^\circ \pm 21^\circ \end{cases}$$
$$\tilde{n} = 0.14 \qquad I_s / I_p = 1.7$$

- Exact values depend on the mirror retardance (being assessed)
- Solution method validated by simulations

Measurement Issues

- Detectible mode frequency is limited to ~40 kHz -- not enough photons in a period to detect
- Due to “busy” spectrum, there are MHD frequencies which can be masked by PEM peaks
- Minimum detectible mode amplitude is estimated to be ~10-20 G. This is possibly limited by the current 12 bit digitizers. Hope to get 16 bit digitizers in the near future
- Other complications
  - Large amplitude (observable) modes don’t linger, so the time the mode is stationary is generally short, typically < 50 ms, making measurements noisy due to short integration time
  - ELMs also contribute considerably to the background noise

Toroidal Correlations in the Magnetic Pitch Angle Fluctuations could be Studied with a Second Fast MSE System

- Two toroidally separated fast MSE systems would allow the study of toroidal correlations in the pitch angle fluctuations
- Applicable to both
  - NTMs
  - Edge phenomena (EHO, ELMs, Stocastisized SOL, …)
- Plan to migrate entire MSE data acquisition system (64 channels) to a 16 bit fast (500 kHz) system (eliminate all CAMAC and analog components)

Summary

- MHD oscillations have been observed on the MSE diagnostic using a fast data acquisition system
- The diagnostic is sensitive to density as well as pitch angle fluctuations preventing direct interpretation of the data
- An analysis technique has been developed to interpret the data and has been applied to it with some success - further work is needed here
- This allows the local values of the phase and amplitude of magnetic fluctuations to be determined
- We are currently limited by the sensitivity of the diagnostic, but plan to improve this in the near future