

PSFC/JA-05-02

**Real Time Control of the
Active MHD Diagnostic on Alcator C-Mod**

W. Burke, W. Cochran, J. Sears,
J. Snipes, S. Wolfe, X. Zhong

29 September 2005

**Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139 USA**

This work was supported by the U.S. Department of Energy, Cooperative Grant No. DE-FC02-99ER54512. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Submitted for publication to *Proceedings of the 21st IEEE/NPSS Symposium on Fusion Engineering, Knoxville TN USA, 2005.*

Real Time Control of the Active MHD Diagnostic on Alcator C-Mod

W. Burke, W. Cochran, J. Sears, J. Snipes, S. Wolfe, X. Zhong,
MIT Plasma Science and Fusion Center, 190 Albany Street, Cambridge, MA 02139

Abstract— An Active MHD Diagnostic has been installed and operated on Alcator C-Mod to study Toroidal Alfvén Eigenmodes (TAEs). The diagnostic consists of two broadband amplifiers and two antennas which can excite stable modes in the TAE frequency range. The plasma response to this excitation is measured by existing magnetic fluctuation diagnostics. Analysis of the fluctuation data provides information about the TAE frequencies and damping rates as well as mode structure. The Active MHD diagnostic has evolved since its first operation in 2002, when it could only operate over a limited, preprogrammed frequency band. Recent improvements include automatic tuning to cover frequencies from 100 to 750 kHz, and an interface to the Alcator C-Mod Digital Plasma Control System (DPCS). The DPCS monitors plasma parameters, calculates the nominal TAE frequency, and adjusts the frequency input to the MHD amplifiers, all in real time. Now the Active MHD Diagnostic can measure TAEs over an entire plasma shot. This paper is focused on the requirements and design of the MHD Amplifiers, particularly the tuning bandwidth. It will also present some preliminary results from the recent run campaign.

I. INTRODUCTION

A. Toroidal Alfvén Eigenmodes

Toroidal Alfvén Eigenmodes (TAEs) are MHD phenomena that can contribute to anomalous transport of high-energy fusion particles. This can be problematic in advanced tokamaks, lowering fusion gain and increasing damage to the first wall [1]. We plan to study TAEs on C-Mod by exciting stable modes in the plasma with the Active MHD amplifiers and antennas. We will monitor the plasma response with existing magnetic fluctuation diagnostics, which include 65 magnetic pickup coils distributed toroidally and poloidally around the machine. Analysis of the fluctuation data using synchronous detection (in software) gives the real and imaginary values for the transfer functions between the drive antennas and the individual pickup coils. The TAE frequencies and damping rates are found by fitting polynomials to the transfer functions. TAE mode structure can be inferred by looking at data from multiple pickup coils [2].

The TAE frequencies depend on the toroidal field and plasma density, as well as a number of machine dependent constants. In Alcator C-Mod we have seen TAEs between 150 kHz and 1 MHz. The TAE bandwidths are quite small, on the order of a few percent, which makes them difficult to find. In practice, we need to sweep the MHD excitation frequency

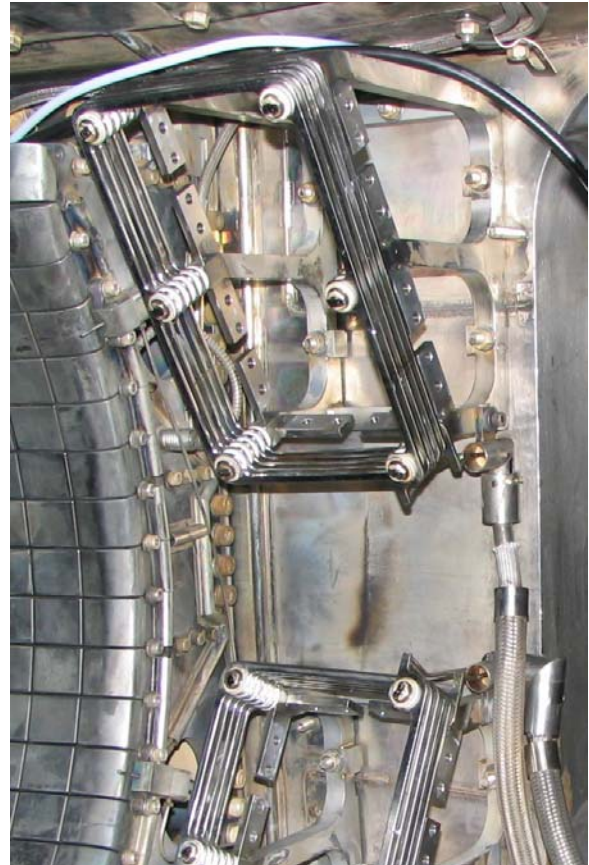


Figure 1. There are two Active MHD Antennas installed in Alcator C-Mod. The top antenna and a portion of the bottom antenna are shown in this photograph.

through the Alfvén frequency to see a resonance. The frequency sweep requirements are set empirically at ± 100 kHz and 2.0 MHz/s.

B. Alcator C-Mod Digital Plasma Control System

The Alcator C-Mod Digital Plasma Control System (DPCS) is a multi-input, multi-output (MIMO) controller running on a Linux computer. The DPCS implements PID loops in software to control a number of plasma parameters including current, density, shape, and position [3].

The DPCS monitors toroidal field and plasma density to calculate the nominal TAE frequency and then superimposes the frequency ramp. It generates a 0-10 V control signal for the MHD Amplifiers scaled at 100 kHz/V.

II. ACTIVE MHD ANTENNA

A. Mechanical Characteristics

The photograph in Fig. 1 shows the two Active MHD Antennas installed in Alcator C Mod. They are mounted on the outboard wall of the vacuum vessel between G- and H ports, one above and one below the midplane. Each antenna is a five-turn rectangular coil, 15 cm by 25 cm. The antennas are positioned approximately 2 cm outside the last closed flux surface.

B. Drive Requirements

The current drive requirement for the MHD antennas has been set empirically at 20 A. This is large enough to find TAEs using synchronous detection, and small to avoid interference with other diagnostics.

C. Electrical Characteristics

The inductance of the MHD Antennas is approximately 9 μH . The resistance varies from 0.4 Ω at dc to 2 Ω at 1 MHz due to skin depth effects. In the TAE frequency range, the antenna impedance is primarily inductive:

$$Z_{\text{ANT}} = R + j \cdot \omega L \quad (1)$$

$$= 1 + j \cdot 8.5 \Omega \quad \text{at 150 kHz} \quad (2)$$

$$= 2 + j \cdot 56 \Omega \quad \text{at 1 MHz} \quad (3)$$

D. Electrical Stresses

The maximum voltage on the MHD antenna and the maximum power dissipation both occur at 1 MHz, which is our highest operating frequency:

$$V_{\text{MAX}} = I_{\text{PEAK}} \cdot |Z_{\text{ANT}}| \quad (4)$$

$$\approx 20 \text{ A} \cdot 56 \Omega = 1100 \text{ V} \quad (5)$$

$$P_{\text{MAX}} = \frac{I^2 R}{2} \quad (6)$$

$$= \frac{(20 \text{ A})^2 \cdot 2 \Omega}{2} = 400 \text{ W} \quad (7)$$

The peak voltage raises some design issues for the antennas, which face the plasma in a vacuum, but no serious problems for the amplifiers, transmission lines or matching networks. The power required is actually quite modest. Also note that the duty factor of the MHD antenna is less than one percent, typically 5 seconds of operation every 10 minutes. So the average power dissipation in the antenna is only 4 watts.

E. Tuning Bandwidth

In general, some sort of transmission line and impedance matching network are required between an antenna and an amplifier. The values of matching network components are frequency dependent and must be set properly to drive the antenna.

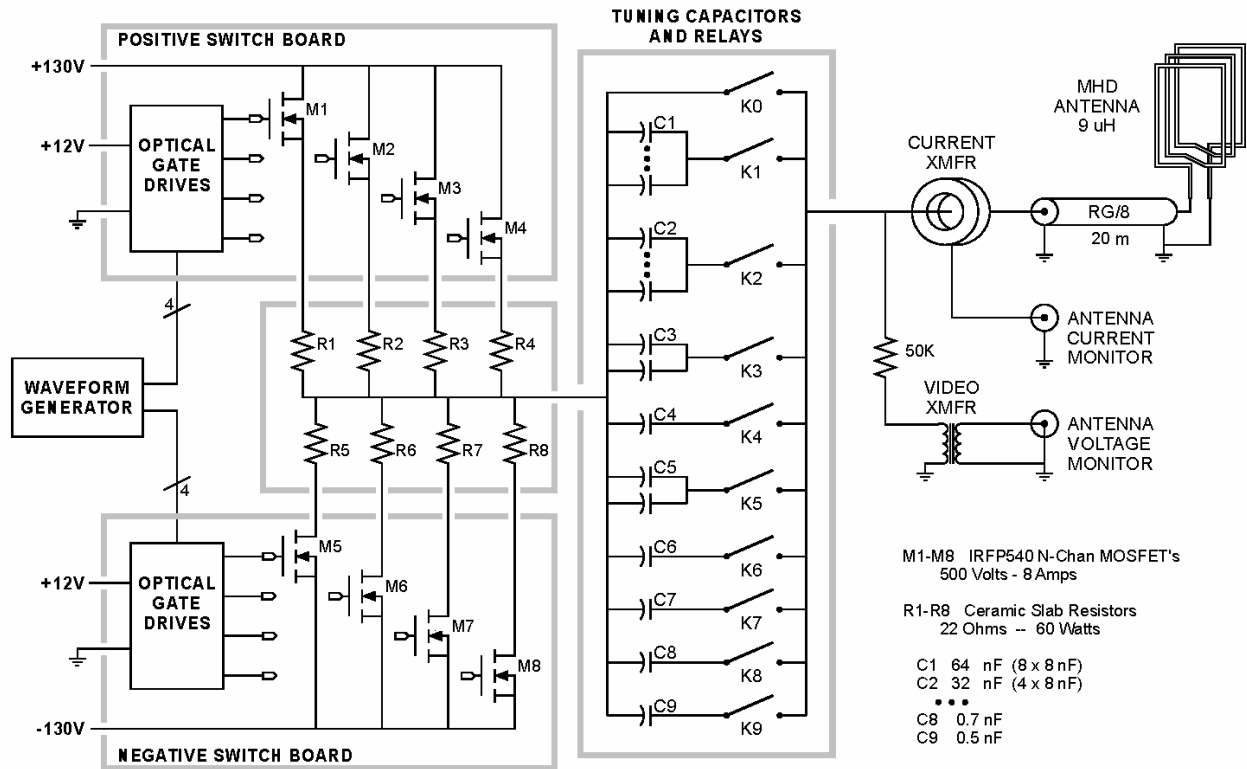


Figure 2. Block diagram for the Active MHD Diagnostic showing one of the amplifiers and antennas. The tuning capacitors and relays, and the output current and voltage monitors are part of the amplifier. The Waveform Generator, which controls the tuning relays and MOSFETs in two amplifiers, is in a separate chassis.

The bandwidth of the MHD antenna is a function of its inductance and resistive loading. Ignoring transmission line effects and assuming a nominal midband resistance of 1.0Ω , the bandwidth on the MHD antennas is simply:

$$BW = \frac{R}{2\pi L} = \frac{1.0 \Omega}{2\pi \cdot 9 \mu\text{H}} = 18 \text{ kHz} \quad (8)$$

Sweeping the MHD frequency $\pm 100 \text{ kHz}$ at 2.0 MHz/s could require on the order of 100 tuning changes per second. Although it might be possible to build such a fast mechanical or electrical matching network, it would certainly be complicated and expensive.

F. Increase Antenna Loading to Improve Bandwidth

Another way to deal with the tuning problem is to load the antenna with a series resistance. This will increase the effective bandwidth at the cost of increased input power.

The C-Mod MHD amplifiers were designed with an output resistance of 5.5Ω . The bandwidth and input power requirements for this loading are:

$$BW = \frac{R}{2\pi L} = \frac{(5.5 + 1.0) \Omega}{2\pi \cdot 9 \mu\text{H}} = 115 \text{ kHz} \quad (9)$$

$$P_{\text{MAX}} = \frac{(20\text{A})^2 \cdot (5.5 + 1.0) \Omega}{2} = 1300 \text{ W} \quad (10)$$

III. ACTIVE MHD AMPLIFIERS

The C-Mod Active MHD Amplifiers were designed and built at MIT, and optimized for driving the Active MHD Antennas. They are robust, inherently stable, and relatively inexpensive [4].

The block diagram in Fig. 2 shows one of the MHD amplifiers and antennas. The tuning capacitor and relays, and the output current and voltage monitors are in the amplifier chassis. There are approximately 20 meters of coaxial cable between the amplifiers and the antennas. The MHD Waveform Generator, which interfaces to the DPCS and drives two amplifiers, is in a separate chassis.

A. Amplifier Design

The C-Mod Active MHD Amplifiers are digitally programmable, bipolar current sources with an output impedance of 5.5Ω , and an output compliance of $\pm 130 \text{ V}$. The output impedance of the amplifier intentionally loads the antenna to improve the bandwidth.

The block diagram in Fig. 2 includes a simplified schematic for the MHD Amplifier. The output stage uses eight N-channel MOSFETs configured as optically isolated switches. Each MOSFET is protected by a 22Ω current limiting resistor. The resistors combine in parallel to set the output impedance. The amplifiers will safely drive 23 A into a short circuit and 20 A into a 1Ω load.

B. Output Waveform

The MHD Amplifier can generate an arbitrary output current waveform by closing the MOSFET switches in the proper sequence. For example, Fig. 3 shows the best fit to a sinusoidal output for a 1Ω load assuming 128 time samples per cycle. The positive peak current is $+20 \text{ A}$ with all four high-side switches closed. The symmetric negative peak current is -20 A with all four low-side switches closed. The output impedance in both cases is:

$$Z_{\text{OUT}} = 22 \Omega / 4 = 5.5 \Omega \quad (11)$$

When all of the switches are open, the output current is zero. However, the output impedance is very high and the load voltage is unconstrained. Interrupting the current in an inductor (the MHD Antenna) predictably generates high frequency switching transients. It is much better to drive the output current and voltage to zero by closing one high-side and one low-side switch simultaneously.

C. Output Harmonics

Fourier analysis of the ideal waveform in Fig. 3 suggests that it is a very good approximation to a sinusoid. The amplitude of the fundamental is 20.3 A . All the even harmonics are zero, as expected. The 5th harmonic is 1.3% of the fundamental. The 3rd, 7th and 9th are all less than 1%.

D. Digital Frequency Synthesis

The output from the MHD Amplifier depends on the precise control of the MOSFET switches. The MHD Waveform generator uses a modified direct digital synthesis (DDS) technique [5]. The block diagram in Fig. 4 shows the DDS logic, which is implemented in three Atmel ATF1500 CPLDs.

The analog TAE frequency command from the DPCS is converted to a 12-bit binary word and stored in the Frequency Register. The Phase Accumulator performs a digital integration of frequency to give the instantaneous phase. The seven most significant bits of the Phase Register control the MOSFET switches, which allows for up to 128 time samples per cycle.

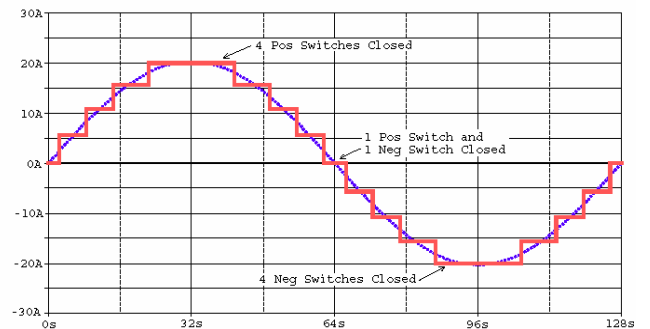


Figure 3. The MHD Amplifier is a class D switching amplifier, but it can still generate a near sinusoidal output.

E. Waveform Generator Specifications

The frequency resolution and range specifications of the Waveform Generator are:

$$f_{\text{MIN}} = \frac{f_{\text{CLOCK}}}{2^{17}} = \frac{32.768 \text{ MHz}}{131,072} = 250 \text{ Hz} \quad (12)$$

$$f_{\text{MAX}} = f_{\text{MAX}} \cdot 4095 = 1.02375 \text{ MHz} \quad (13)$$

The output frequency can change from minimum to maximum in a single clock cycle. In this implementation, the 10 kHz input sampling clock allows a frequency sweep rate of 10 GHz/s.

F. Tuning and Matching

The transmission lines between the Active MHD amplifiers and antennas are fairly short, approximately one tenth of a wavelength at 1 MHz. In the TAE frequency range, the load impedance at the amplifier is always inductive. This allows us to use a simple matching network, i.e. single series capacitance, to cancel the load inductance.

The relays and capacitors that make up the matching network are shown in Fig. 2. The Waveform Generator controls the relays and adjusts the antenna tuning automatically. The switching time for the relays is approximately 20 ms.

A PSpice model was used to look at various tuning configurations. The results are shown in Fig. 5. With no transmission line, the antenna current and tuning bandwidth are independent of frequency. Unfortunately, the transmission line has a significant and adverse effect on bandwidth, reducing it by a factor of two at low frequencies, and by a factor of ten at 1 MHz.

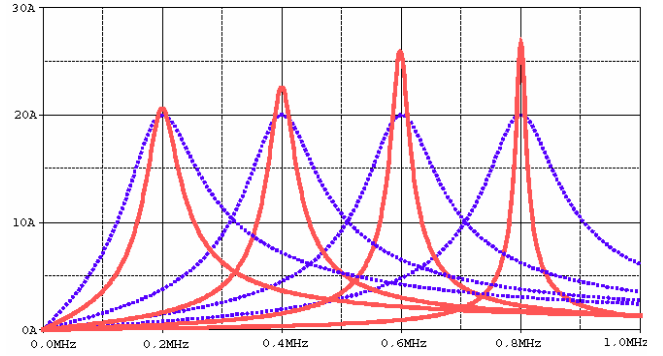


Figure 5. Antenna current as a function of frequency with and without a transmission line. The transmission line reduces the bandwidths at the high end of the range to approximately 10kHz.

IV. ACTIVE MHD DIAGNOSTIC IN OPERATION

The Active MHD Diagnostic ran successfully during the last run campaign. Fig. 6 shows data from C-Mod shot 1050812014 which ran at 5.4 T with a flattop current of 0.8 MA. The shot duration was 1.8 s.

The nominal TAE frequency calculated by the DPCS was close to 500 kHz during the flattop. The MHD frequency swept between 400 and 600 kHz several times.

A. Antenna Current and Tuning

The current in the MHD Antenna was greater than 20 A for approximately half of the shot. The tuning at the low end of the frequency range is clearly better than at the high end. There were at least twenty tuning changes during the shot, and several times when the antenna current dropped below 5 A. The MHD Amplifier may be spending as much as 30% of the time during shot adjusting the tuning.

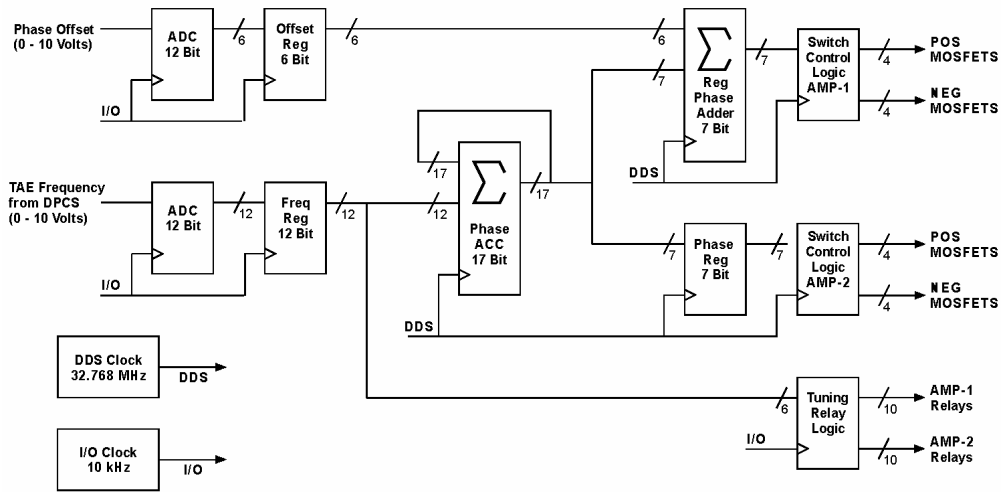


Figure 4. The Active MHD Waveform Generator uses direct digital synthesis (DDS) to generate the switch control signals for both MHD amplifiers. It also includes a look-up table for the tuning relays. All of the logic fits into three Atmel ATF1508 CPLDs.

B. Synchronous Detection

Fig. 6 shows the current in the MHD Antenna and the response of one of the magnetic pickup coils, during the entire shot and on an expanded timescale near the nominal TAE frequency. There is no obvious correlation, but synchronous detection finds a clear resonance. In fact, despite the tuning problems, synchronous detection found TAE resonances on eleven of the twelve frequency ramp segments during the shot.

V. FURTHER WORK

From an operational viewpoint, the most annoying problems with the Active MHD Diagnostic are narrow bandwidth and the number of tuning changes required during a shot. There are a few ways to improve the performance:

Move the amplifiers closer to the antennas. This will certainly improve bandwidth, but it is not always practical.

Reduce the time required for tuning changes. Since the MHD Amplifiers are digitally controlled, it might be possible to use two amplifiers to cover the TAE frequency range in alternating bands. The time required to switch between adjacent bands could be on the order of 10 μ s. This would require more amplifiers. But we would use the existing power supply, which is the single most expensive part of the diagnostic.

Increase the antenna loading. The design of the MHD Amplifiers can probably accommodate a fourfold increase in output resistance and compliance voltage. This would require new amplifiers as well as a larger and more expensive power supply.

REFERENCES

- [1] J. Snipes, "Fast particle driven modes in Alcator C-Mod," in Proc. 26th EPS Conference on Controlled Fusion and Plasma Physics, June 1999, European Physical Society.
- [2] D. Schmittiel, "Investigation of Alfvén Eigenmodes in Alcator C-Mod using active MHD spectroscopy," May 2003, MIT Nuclear Engineering Department Master Thesis.
- [3] J.A.Stillerman, M.Ferrara, T.W.Fredian, S.M.Wolfe, "Digital real time control system for Alcator C-Mod," Fifth IAEA Technical Meeting (IAEA-TM) on Control, Data Acquisition, and Remote Participation for Fusion Research, July 2005, Budapest, Hungary, Fusion Engineering and Design, in press.
- [4] W. Burke, W. Cochran, D. Schimttiel, J. Snipes, X. Zhong, "Broadband Amplifiers for the Active MHD Diagnostic on Alcator C Mod", 20th IEEE/NPSS Symposium on Fusion Engineering (SOFE), San Diego, CA, Proceedings, pp 363-366
- [5] J.A.Webb, "Digital Signal Generator Synthesizer," U.S Patent 3,654,450, Application filed in 1970.

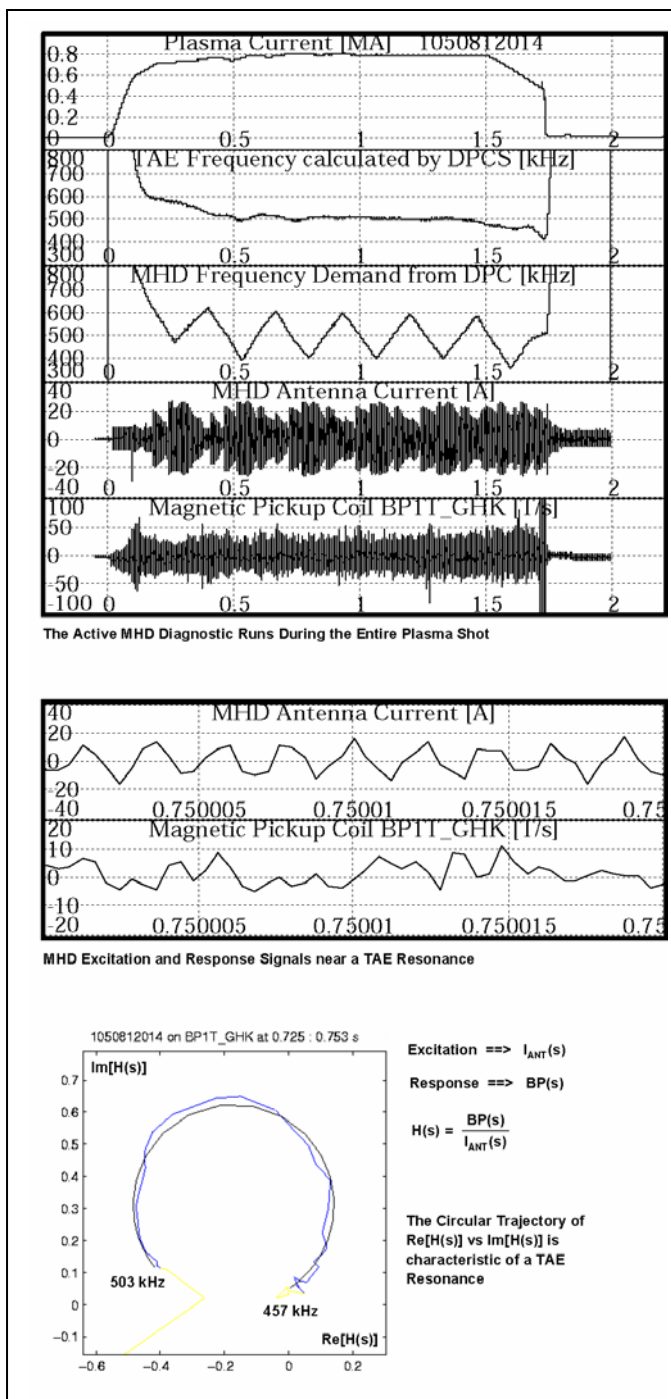


Figure 6. The Active MHD Diagnostic was able to identify numerous TAE resonances over the course of this plasma shot.