Microwave Imaging Reflectometry for the study of Edge Harmonic Oscillations on DIII-D

X. Ren, M. Chen, X. Chen, C.W. Domier, N.M. Ferraro, G.J. Kramer, N.C. Luhmann, Jr., C.M. Muscatello, R. Nazikian, L. Shi, B.J. Tobias and E. Valeo

University of California at Davis, 1 shield Avenue, Davis, CA, U.S.A., 95616
General Atomics 3483 Dunhill St, San Diego, CA, U.S.A. 92121
Princeton Plasma Physics Laboratory 100 Stellarator Rd., Princeton, NJ, U.S.A. 08540

E-mail: xren@ucdavis.edu

ABSTRACT: Quiescent H-mode (QH-mode) is an ELM free mode of operation in which edge-localized harmonic oscillations (EHOs) are believed to enhance particle transport, thereby stabilizing ELMs and preventing damage to the divertor and plasma facing components. Microwave Imaging Reflectometer (MIR) enabling direct comparison between the measured and simulated 2D images of density fluctuations near the edge can determine the 2D structure of density oscillation, which can help to explain the physics behind EHO modes. MIR data sometimes indicate a counter-propagation between dominant ($n=1$) and higher harmonic modes of coherent EHOs in the steep gradient regions of the pedestal. To preclude diagnostic artifacts, we have performed forward modeling that includes possible optical mis-alignments to show that offsets between transmitting and receiving antennas do not account for this feature. We have also simulated the non-linear structure of the EHO modes, which induces multiple harmonics that are properly charaterized in the synthetic diagnostic. By excluding mis-alignments of optics as well as partially eliminating non-linearity of EHO mode structure as possible explanation for the data, counter-propagation observed in MIR data, which is not corroborated by external Mirnov coil array measurements, may be due to subtleties of the eigenmode structure, such as an inversion radius consistent with a magnetic island. Similar effects are observed in analysis of internal ECE-Imaging and BES data. The identification of a non-ideal structure motivates further exploration of nonlinear models of this instability.

A shorter version of this contribution is due to be published in PoS at:
1st EPS conference on Plasma Diagnostics

KEYWORDS: Models and simulations; Simulation methods and programs; Plasma diagnostics - interferometry, spectroscopy and imaging
1 Introduction

Quiescent H-mode [1–3] is one possible operation mode for future fusion reactors, such as ITER. It preserves superior energy confinement while also preventing damage to divertor and other plasma facing components by avoiding ELMs. Edge Harmonic Oscillations (EHOs) [4–7] are coherent fluctuations of the edge plasma having low toroidal mode number, e.g. 1-3, as determined by Mirnov coil arrays. They are believed to be the key element of QH-mode, enhancing particle transport at the edge and allowing the edge plasma to reach equilibrium below the ELM stability boundary. Figure 1 shows an example (DIII-D shot # 157102) of QH-mode without ELMs versus a typical H-mode (DIII-D shot # 154412) with strong ELMs. Recent theory predicts that EHO is a low-n peeling mode with its stability closely tied to toroidal rotation shear [2, 3].

The Microwave Imaging Reflectometer (MIR) [8, 9] on DIII-D is an X-mode imaging reflectometer, with tunable frequency range from 56 to 74 GHz and 20 cm poloidal coverage. MIR is well suited for measuring density fluctuations in the steep gradient pedestal region of H mode and has been used to compare the poloidal wavenumber spectra of both the coherent and so-called broadband EHO types [10]. These measurements could help to validate a model for EHO excitation and control, as MIR data often exhibits unique features when compared to other diagnostics. Apparent broadening of wavenumber spectra at the frequency of the dominant $n = 1$ mode is observed in MIR data when imaging near the top of the pedestal. This causes the poloidal wavenumber, $k_{pol}$, to sometimes take on negative values in the image, and hence appear to propagate in the counter direction compared to the higher toroidal modes ($n > 1$). However, this phenomenon is not reflected in Mirnov coil array data, which is external to the plasma. Figure 2 shows MIR measurements from two frequency/radial channels for discharge # 157102, which is configured with normal Bt, reversed Ip, and counter-current neutral beam torque. The frequency profile in figure 2(a) is obtained from a fit to temperature/density profile data from conventional ECE and Thomson scattering. All the toroidal harmonic modes diagnosed with the 57 GHz channel, which is located near the edge of plasma as shown in figure 2(b), have the same direction of propagation (the direction of toroidal torque), and this co-propagation is also observed and consistent with Mirnov coil array data. However, for the channel at 58 GHz, which is located more inside the plasma and near the top of pedestal, the distribution of poloidal wavenumber is broadened, with average values opposite
Figure 1. Examples of quiescent H-mode (left) and conventional H-mode (right). The quiescent H-mode has strong coherent EHOs measured with MIR (upper left), and no bursts of $D_\alpha$ radiation at the divertor (lower left). The conventional H-mode is ELMing with frequent spikes of $D_\alpha$ emission (lower right). MIR measured inter-ELMing modes has higher frequencies (upper right) for conventional H-mode.

Figure 2. Apparent broadening of spectra of coherent EHO mode $n=1$ observed in MIR data. Shown in (a) are the characteristic frequencies with respect to major radius, obtained from a fit to temperature/density profile data from conventional ECE and Thomson scattering; location of MIR 57 and 58 GHz channels are also highlighted. The dominant mode and harmonics measured with the 57 GHz channel (b) are propagating in the same direction. However, data from the 58 GHz channel (c), located more near the top of pedestal, measures the dominant mode ($n=1$) with strongly broadening in spectra and results in negative $k_{pol}$ to higher harmonics ($n=3$, etc.). This produces an apparent counter-propagation compared to other toroidal harmonic modes. This counter-propagation could be real and due to subtleties of EHO modes on the top of pedestal, or it could come from instrumental artifacts. Possible sources of instrumental artifacts are investigated using forward modeling of MIR; however, they do not reproduce the observed effect of causing counter-propagation, leading us to suspect that they are in fact due to subtleties of the EHO modes.
Figure 3. The process of forward modeling MIR diagnostic output from the 3D MHD code M3D-C1. Time-dependent output of coherent EHO modes from M3D-C1 has been provided for shot #157102 with different toroidal mode number \( n = 3 \) or 5. The perturbed plasma profiles are used as input for FWR. Antenna patterns taken from the diffractive modeling of MIR imaging optics are used as boundary conditions for the simulation. The converged electric field pattern at the outgoing microwave boundary is taken at each time step of the simulation and compared with the receiver antenna pattern to produce a quadrature (amplitude and phase) signal time point.

2 Forward modelling of MIR

The synthetic MIR [11] diagnostic provides a powerful tool to accurately simulate the output of the diagnostic, thus, helping to interpret instabilities and is employed to investigate optical arrangements and possible instrumental artifacts. This forward modeling of MIR is realized with the combination of three components: plasma profile with turbulence, full-wave reflection codes FWR [12, 13] and MIR optics. The plasma profile could be obtained from simulation output, or equilibrium profile with experimentally measured edge perturbations, from, say, edge magnetics sensors, electron cyclotron emission (ECE) radiometer, ECE-Imaging (ECE-I) or MIR. The FWR codes are used to simulate sub-THz wave interaction with the prescribed plasma. FWR2D code calculates reflection in the poloidal plane and is well established and extensively used, while the 3D version, which is still under development and not extensively used, calculates reflection over an extended 3D volume in plasma. Simulation results from FWR2D, due to its better stability, are presented in the following content. The beam field applied in FWR is generated from diffraction modeling of the MIR optics employing beamlet-based wave propagations.

The method of generating synthetic diagnostic signals from plasma simulation output is illustrated in figure 3 below. A time-series (or periodic sequence) of perturbed electron density data from simulation is combined with the optical field patterns of the diagnostic to produce time-dependent synthetic imaging data. Thousands of time-points can be generated with the usage of an efficient algorithm of the full-wave reflection code FWR2D, which utilizes a very efficient paraxial-wave solution to solve for propagation in the low field side plasma regions far off the cutoff. The reflected field from FWR is combined with the MIR receiver beam field to produce a synthetic diagnostic signal, resolving phase/density fluctuations on the cutoff layer. Synthetic imaging data may be analyzed by the same methods applied to real data on DIII-D in order to understand the diagnostic response and features of the visualization.
Figure 4. Synthetic images of phase perturbation (lower row) produced by synthetic diagnostic and images of cutoff layer displacement (upper row) due to density perturbation from M3D-C1 simulation output. The $n = 3$ electron density fluctuation produced by M3D-C1 is shown at left. This perturbation is evolved in time to produce the images in the top row from an idealized MIR diagnostic with 7 probing frequencies. The perturbation on the upper row is nearly indistinguishable with the lower row in both mode structure and rotation velocities with scaled phase and displacement perturbation.

3 Forward modeling of instrumental non-idealities

Examples of synthetic images produced by the synthetic diagnostic are given in figure 4, with the upper row representing plasma simulation results, and lower row representing forward modeling results. Probing frequencies range from 55 to 61 GHz with 1 GHz intervals, and cover the top pedestal region where the peak of the fluctuation amplitude resides. There are 12 poloidally evenly spaced channels in each frequency/density channel, and each poloidal channel has a spot size approximately 3.0 cm. Note that the poloidal coverage is only 20 cm, much less than the wavelength of the most destabilized coherent EHO modes ($n \leq 5$), making it challenging to resolve the long wavelengths ($k_{pol} \sim 0.1/cm$). The 3D MHD code M3D-C1 [14, 15] is being used to model the QH-mode on DIII-D with the presence of a low-$n$ ($< 5$) EHO mode. It would return one coherent EHO mode with the fastest growth rate for each given toroidal mode number ($n = 3$ or 5 in this paper). M3D-C1 does not obtain a saturated toroidal mode number $n = 1$ or $n = 2$ mode for shot # 157102; thus, the destabilized higher modes $n = 3$ and $n = 5$ are applied. As shown on figure 4, by scaling the phase of the reflectometer signal (lower row) appropriately with the cutoff layer displacement (upper row) due to density perturbation, the two sequences are nearly indistinguishable in both mode structure and rotation velocities, indicating that the forward modeling accurately resolved the input density fluctuations. The peak density fluctuation associated with the coherent EHO fluctuation from M3D-C1 simulation is located at 2.26 m, while the measured maximum fluctuation in the synthetic MIR signal is at 2.258 m, with only 2 mm difference. This difference is due to the fact that the peaked fluctuation is located between two probed cutoff layers. Since the counter propagation observed in MIR data measured near the top of pedestal could be due to either imperfections of the instrument, or subtleties of the eigenmode structure, instrument imperfections as well as partially non-uniform rotation of coherent EHO modes are investigated.
Figure 5. Poloidal wavenumber distribution along the radial direction obtained from (a) M3D-C1 output, (b) forward modeling output with ideal optical alignment and (c) forward modeling output with mis-aligned optics. This measurement becomes less certain when modest optical misalignments are introduced, but the peak of the distribution still remains centered around the expected value.

with three different forward modeling setups: linear EHO modes with ideal MIR optics, linear EHO modes with mis-aligned MIR optics, and nonlinear EHO mode with ideal MIR optics.

Linear EHO $n = 3$ and $n = 5$ modes located near the edge, are destabilized within M3D-C1 simulations, and with their fluctuation amplitude increased to the experimental level (around 5.2 mm maximum radial perturbation, one free space wavelength of probing wave) are measured with MIR forward modeling with and without optical misalignment. Figure 5 shows the wavenumber distribution over each frequency/radial channel for mode $n = 3$. The two most inside radial channels, with smallest fluctuation amplitude, show different wavenumbers to the other edge channels, and this is due to some subtleties in their mode structure. Since these two channels are well inside the pedestal region where dominant EHO is located, this unforeseen difference in wavenumber from simulation is reasonable. Figure 5 (c) shows the wavenumber distribution when transmitter and receiver are mis-aligned by 4 cm vertically. Compared to the case when receiver and transmitter in figure 5 (b) are well aligned, the wavenumber seems distributed more widely, while the peak value of the wavenumber is still measured correctly.

Thus, vertical offsets between transmitter and receiver antennas, as shown in figure 5, does not account for the observed counter-propagation. Both M3D-C1 output and forward modeling yield center wavenumber $k$ around 6.6 rad/m for $n = 3$. The experimental measurement of the wavenumber for the mode $n = 1$ in co-propagation condition is 2.5 rad/m, which is around 1/3 times of that of $n = 3$. This means the $n = 3$ mode has similar phase velocity as that of the $n = 1$ mode. However, experimental measurement of the $n = 3$ EHO component gives a local poloidal wavenumber of $\sim 3.14$ rad/m, which is less than that predicted by the forward modeling of M3D-C1 data. This uncertainty as well as observed counter-propagation may be due to the non-sinusoidal nature of the density fluctuation in experiment, which is not inherent to the M3D-C1 result. This has been partially explored by varying the time dependence of the oscillation of linear EHO mode.
Figure 6. Wavenumber distributions of linear (a) and nonlinear (b) time-dependent fluctuations. (c) and (d) shows the corresponding wavenumber distribution from forward modeling for the dominant and 2nd harmonic of $n = 3$, while both yield the correct center wavenumber.

The magnetic flux displacement obtained from M3D-C1 output is close to:

$$d(x,t) = a_0 \cos(\omega t + \Delta \Phi(x)) + \Delta d \quad \text{with} \quad \Delta \Phi(x) = kx + \phi_0$$

(3.1)

Higher $x$ is the poloidal position and $t$ is time, and is represented by degree in figure 6. Higher fluctuation components, with their amplitudes less than half of that of the dominant $n = 3$ component, are added to manipulate the mode structure:

$$d(x,t) = a_0 \cos(\omega t + \Delta \Phi(x)) + a_1 \cos(2 \ast \omega t + 2 \ast \Delta \Phi(x)) + a_2 \cos(3 \ast \omega t + 3 \ast \Delta \Phi(x)) + \cdots + a_6 \cos(7 \ast \omega t + 7 \ast \Delta \Phi(x)) + \Delta d$$

(3.2)

with $a_0 \geq 2 \ast a_1 \geq \cdots \geq 2^6 \ast a_6$

Figure 6 (a) and (b) show the mode structure for both linear/sinusoidal and nonlinear/non-sinusoidal perturbations. Forward modeling of the non-sinusoidal mode shows that harmonic wavenumber can still be diagnosed correctly, as highlighted in figures 6 (c) and (d). Therefore, this may not be the cause of apparent counter-propagation. Since the experimental fluctuation has a dominant mode number of $n = 1$, which is not destabilized from M3D-C1 simulations for shot 157102, mode structures that are more close to the experimental measured mode structure are needed. Further exploration with FWR3D is warranted to determine the remaining uncertainties.

Since the forwarding modeling indicates that neither misalignment between the transmitter and receiver antennas nor non-sinusoidal time dependence of the EHO modes ($n > 2$) accounts for the broadening of the measured spectra and thus counter-propagation, we are led to speculate as to whether the counter-propagation of the dominant EHO mode is a similar diagnostic artifact as seen in ECE-I data [16], which is known to correspond with a fluctuation phase jump due to magnetic islands. This weak tearing parity has been overlooked in the past, but a similar feature has now been observed in beam emission spectrometer (BES) and other ECE data, as shown in figure 7.
Figure 7. Phase jump observed in both ECE and BES data. As the coherent EHO mode ($n = 1$) decreasing towards into plasma, before its disappearance, an obvious phase jump is captured for shot # 157102. Within this region, $n = 1$ wavenumber distribution measured by both ECE-I and MIR is broadened, resulting in poloidal wavenumber, $k_{pol}$, of opposite sign when compared to other higher toroidal modes.

The MIR artifact signal may be due to the similar phase jump in density fluctuations caused by EHO near the top of pedestal.

4 Summary and Future work

MIR on DIII-D measures detailed characteristics about EHO, which measured both co-propagation and counter-propagation of coherent EHO harmonic modes. Using forwarding modeling, both optical mis-alignment and non-uniform rotation of sub-dominant ($n > 2$) EHO modes are investigated as possible sources of instrumental artifacts, but they do not reproduce the data. The observed counter-propagation of the $n = 1$ mode in MIR data near the top of the pedestal may still be a diagnostic artifact due to phase jumps in the radial eigenfunction of the EHO, which would be consistent with observations from ECE-Imaging and BES. More sophisticated, nonlinear models, applying both FWR2D and more advanced FWR3D, will be applied to explore remaining uncertainties. FWR3D takes toroidal magnetic field pitch as well as wave polarization into account, and will be used to investigate what impacts these 3D effects would have on the reflectometry measurements results.

Acknowledgments

This work is supported by US DoE grants DE-AC02-09CH11466, DE-FG02-99ER54531, DE-FC02-04ER54698 and DE-SC0012551.
References

[1] K.H. Burrell et al., *Quiescent H-mode plasmas in the DIII-D tokamak*, Plasma Phys. Contr. F. 44 (2002) A253.

[2] K.H. Burrell et al., *Edge pedestal control in quiescent H-mode discharges in DIII-D using co-plus counter-neutral beam injection*, Nucl. Fusion 49 (2009) 085024.

[3] K.H. Burrell et al., *Quiescent H-Mode Plasmas with Strong Edge Rotation in the Cocurrent Direction*, Phys. Rev. Lett. 102 (2009) 155003.

[4] A.M. Garofalo et al., *Advances towards QH-mode viability for ELM-stable operation in ITER*, Nucl. Fusion 51 (2011) 083018.

[5] L.J. Zheng et al. *Low-n magnetohydrodynamic edge instabilities in quiescent H-mode plasmas with a safety-factor plateau*, Nucl. Fusion 53 (2013) 063009.

[6] L. Zeng et al., *Dynamic of pedestal perturbations by ELMs and edge harmonic oscillations in DIII-D*, Plasma Phys. Contr. F. 46 (2004) A121-A129.

[7] Z. Yan et al., *High-Frequency Coherent Edge Fluctuations in a High-Pedestal-Pressure Quiescent H-Mode Plasma*, Phys. Rev. Lett. 107 (2011) 055004.

[8] C.M. Muscatello et al., *Technical overview of the millimeter-wave imaging reflectometer on the DIII-D tokamak*, Rev. Sci. Instrum. 85 (2014) 11D702.

[9] C.M. Muscatello et al., *Multi-dimensional visualization of turbulence in fusion plasmas*, IEEE Trans. Plasma Sci. 42 (2014) 2734.

[10] X. Chen et al. *Understanding the physics of EHO in QH-mode on DIII-D Including the Role of Rotation Shear*, talk presented at the 42nd EPS Conference on Plasma Physics, P5.122.

[11] X. Ren et al., *Process to generate a synthetic diagnostic for microwave imaging reflectometry with the full-wave code FWR2D*, Rev. Sci. Instrum. 85 (2014) 11D863.

[12] E.J. Valeo, G.J. Kramer and R. Nazikian, *Two-dimensional simulations of correlation reflectometry in fusion plasmas*, Plasma Phys. Contr. F. 44 (2002) L1.

[13] G.J. Kramer, R. Nazikian and E. Valeo, *Effects of two-dimensional and finite density fluctuations on O-X correlation reflectometry*, Plasma Phys. Contr. F. 44 (2002) L11.

[14] N.M. Ferrara et al., *Calculations of two-fluid magnetohydrodynamic axisymmetric steady-states*, J. Comput. Phys. 228 (2009) 7742.

[15] S.C. Jardin et al., *The M3D-C1 approach to simulating 2-fluid magnetohydrodynamics in magnetic fusion experiments*, J. Phys. Conf. Ser. 125 (2008) 012044.

[16] B. Tobias et al., *Phase-locking of magnetic islands diagnosed by ECE-imaging*, Rev. Sci. Instrum. 85 (2014) 11D847.