Millimeter-wave imaging reflectometry on the DIII-D tokamak

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Abstract. A new multi-channel, multi-frequency mm-wave imaging reflectometer (MIR) has been installed on DIII-D with the purpose of diagnosing density fluctuations in two-dimensions with unprecedented sensitivity and resolution. This diagnostic is an extension of quasi-optically imaged reflectometry to 2D with twelve vertically separated sightlines and four-frequency operation (corresponding to four radial channels). Features that distinguish the 48-channel DIII-D MIR system are: 1) illumination frequencies that can be tuned within 500 μs over a range of 56 to 74 GHz, 2) an innovative optical design that keeps both on-axis and off-axis channels focused at the cutoff surface, and 3) shared port with electron cyclotron emission imaging, thereby permitting simultaneous measurements of electron temperature and density in the same volume of plasma. These key features permit visualization and quantitative diagnosis of density perturbations, including correlation length, wavenumber, mode propagation velocity, and dispersion. During its initial experimental campaign on DIII-D, MIR has provided images of various magnetohydrodynamic modes that occur in the interval between edge-localized modes during advanced inductive H-mode discharges. Analysis of these modes is used to illustrate just some of the possibilities with this new diagnostic capability, while particular emphasis is given to mode rotation in both the plasma and laboratory frames.

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1. Introduction

Reflectometry is an active, radar-like diagnostic technique frequently employed to probe local properties of the electron density in fusion plasmas [1-3]. Besides its high sensitivity to density fluctuations, reflectometry provides a localized measurement, relying on the reflection of a microwave beam from the cutoff surface, an opaque layer in the plasma where the index of refraction goes to zero at the probing frequency. When properly coupled, the reflected beam is phase-modulated by fluctuations of the index of refraction near the cutoff surface. For X-mode polarization, the frequency, shape, and location of the cutoff layer depend on both the electron density and total magnetic field. Proper coupling may be accomplished by optical imaging [3-5].

Quasi-optical imaging at sub-THz frequencies has had a major impact on fusion plasma diagnostics. While electron cyclotron emission imaging (ECE-Imaging) focuses emission from the plasma onto a heterodyne detector array to perform 2D radiometry of electron temperature fluctuations [6,7], similar techniques applied to reflectometry focus both the illumination beam and the signals reflected from the cutoff surface. This means taking a spatially resolved "picture" of the fusion plasma. Probing the plasma simultaneously with multiple frequencies produces a 2D image of turbulence and magnetohydrodynamic (MHD) eigenmodes. It allows for analysis of radial and poloidal correlation lengths, wavenumbers, and both the phase and group velocity of propagating modes. It does not rely on auxiliary tokamak systems (such as neutral particle beams), and the probing radiation does not perturb the plasma while the diagnostic monitors changes in density throughout the discharge.

Mm-wave imaging reflectometer (MIR) is well-suited for diagnosing fluctuations in the edge region of H-mode plasmas. Thorough diagnosis of edge localized modes (ELMs) is important for model validation and for measuring the evolving ELM characteristics during suppression and mitigation techniques. The constraints that the edge harmonic oscillator (EHO) imposes during quiescent H-mode plasmas and its effect on particle confinement are still not well understood. With MIR, coupled with ECE-Imaging, unambiguous images of the perturbation induced by the EHO could help to elucidate its spatial and spectral structure as well as the cross-phase between electron density and temperature, leading to potentially important information regarding transport. Beyond ELMs and the EHO, MIR and ECE-Imaging are useful for monitoring the edge plasma response to externally impose magnetic perturbations (such as those used for ELM suppression) and the edge response to core-localized MHD such as tearing modes. Among its multi-faceted capabilities, MIR also has the potential for being a general diagnostic for measuring the edge rotation profile.

This paper is intended to provide an overview of the MIR system installed on the DIII-D tokamak [8]. In section 2, specifications of the system are discussed, including its accessibility in DIII-D plasmas, a novel design for the detector array, a brief overview of the electronics, and a summary of operational parameters. In section 3, data gathered during an ELMing advanced inductive H-mode discharge will be presented to demonstrate some of the analysis that may be performed with MIR data. Spectrograms from MIR and other diagnostics are compared. Simultaneous 2D images from MIR and ECE-Imaging are obtained for selected coherent modes. Representation of the fluctuations in velocity space allows for a comparison of mode propagation and the rotation of the plasma. Along with a summary of these observations, planned upgrades to the DIII-D MIR system are discussed in section 4.

2. Millimeter-wave Imaging Reflectometry on DIII-D

The two-dimensional MIR system was installed on DIII-D in May 2013 and began taking plasma data in July 2013. It is designed to take full advantage of the large aperture port it shares with the ECE-Imaging diagnostic [9] to access large regions of the plasma. A broad frequency range (56 – 74 GHz) and 12-element antenna array map to a poloidal cross-section of the plasma. The diagnostic probes the right-handed X-mode (RX) cutoff, access to which depends on the relative frequency of cyclotron resonances in the plasma. Frequency-versus-major radius is plotted in the left panel of figure 1 for various resonances and cutoffs in a DIII-D H-mode plasma (shot 154412). The O-mode and RX cutoffs are shown as well as the first two harmonics of the electron-cyclotron and upper-hybrid (UH) resonances. The horizontal dashed lines indicate the frequency range of MIR, from which the accessible radial range can be extrapolated. It should be noted that, since the RX cutoff depends on the local values of the electron density and magnetic field, variations in these profiles lead to modifications to the radial accessibility. The right panel of figure 1 is an elevation of a portion of the poloidal cross-section of the plasma, showing the tokamak vessel wall, last-closed flux surface, RX cutoff, and UH resonance. The transmitted frequencies from MIR must pass through the intervening plasma without being absorbed at the resonances. The proximity of the UH resonance layer imposes another constraint on MIR. Although the UH resonance always lies at smaller major radius than the RX cutoff, mode conversion can occur if it is sufficiently close to the cutoff layer, thereby allowing the evanescent wave to tunnel in and out of this region and complicating the interpretation of the reflected signal.

For the best possible coupling of radiation reflected off the plasma target, the detector's imaging plane, i.e. the receiver antenna array, is shaped to be an image of the target, i.e. a curved surface (figure 2). For most DIII-D plasmas, the shape of the RX cutoff layer within the MIR viewing window is very nearly circular, so each antenna element lies on an arc of a circle. The curvature of the arc is determined with Gaussian beam tracing by minimizing the total distance between each of the individual focal points and the cutoff surface. The curvature of the detector array compensates not only for the curvature of the cutoff surface, but also for the difference in optical path length for center and edge channels that appears as a spherical aberration. The result is a near normal viewing angle at the cutoff surface for most channels. Combined with shaping of the illuminating probe beam, each of the 12 detectors observes a specular reflection.

Evaluation of the MIR optical system and the response of the diagnostic to simple, model fluctuations are possible at each stage of the design with synthetic diagnostic modeling. Specifically, the full-wave reflectometer code FWR2D [10,11] has been used to simulate the plasma-wave interaction under prescribed conditions and to optimize the design for diagnosis of the greatest possible range of mode amplitude and wavenumber. The details of this iterative design process, aided by synthetic diagnostic modeling, are presented in reference [12]. Table 1 summarizes the parameters of the current MIR system on DIII-D based on a combination of synthetic modeling and laboratory characterization. In order to remove the ambiguity associated with an implied factor of radians in some definitions of wavenumber, in this paper it is defined as inverse wavelength with units of cycles per meter.

Figure 3 is a schematic illustrating MIR source generation, detection of the reflected signal, down-conversion, and quadrature mixing resulting in so-called I/Q output. The multi-frequency MIR source is generated by up-converting two sources (tunable over the range of 0.5 to 9.0 GHz with 10 MHz resolution and a switching speed of less than 500 μs) with a Gunn oscillator source centered at 65.00 GHz. This is illustrated for one radio frequency (RF) source, producing two probe frequencies. With two RF sources, double-sideband up-conversion generates four frequencies centered about 65.00 GHz whose exact values can be programmed depending on the needs of the experiment. Each imaging antenna collects the reflected multi-frequency MIR signal and down-converts this to an intermediate frequency (IF) in the range of 0.5 to 9.0 GHz. The down-conversion is accomplished on the antenna board by a GaAs Schottky diode mixer for each antenna. A portion of each of the 65.00 GHz and 65.37 GHz signals produced by Gunn oscillators in the machine hall are collected by a reference mixer and are used to decode/demodulate the IF signals. This is accomplished by new, multi-layer, mixed-signal IF modules [figure 3(c)] designed at UC Davis. In-phase-quadrature (I/Q) mixers (also known as demodulators) produce a pair of signals for each probe frequency. These signals correspond to $A \cos\phi$ and $A \sin\phi$, from which amplitude (A) and phase (ϕ) modulation due to reflection at the plasma may be derived.

3. MIR data analysis – Inter-ELM fluctuations

In this section we demonstrate several analysis techniques for MIR data to illustrate the range of capabilities that this innovative diagnostic provides. Discharge 154412 is an

ELMing H-mode with $B_t = +2.1$ T. This is referred to as “reversed B_t,” with toroidal magnetic field in the same direction as the plasma current. The discharge is fully non-inductive, with inductive loop voltage near zero for much of the 0.53 MA current flat-top. The ELMs in these scenarios are accompanied by a rich spectrum of MHD behavior that is detected by multiple diagnostics and which in large part remains an active area of investigation.

3.1. Processing of quadrature heterodyne signals

As density and magnetic field evolve throughout the discharge, cutoff surfaces may move in and out of a particular focal plane. Without real-time focusing (a topic of ongoing research [13]), MIR image quality varies with variation of the plasma profiles. A useful metric for assessing imaging quality is direct monitoring of the reflectometer signal components, I and Q. The I and Q signals are the direct signal mixed with the reference local-oscillator (in-phase) and that of the signal phase-delayed by 90° and mixed with the same reference (quadrature). In terms of the amplitude, *A*, and modulated phase, □, of the reflected wave coupled to the imaging receiver, I and Q are taken to be,

$$I = A \cos \phi \tag{1a}$$
$$Q = A \sin \square \quad . \tag{1b}$$

Phase jumps of ±π due to branch points in cosine and sine are unwrapped in order to evaluate the absolute phase relative to some reference phase, and any dc offsets can be corrected in the I/Q plane by high-pass frequency filtering. In the phase-screen model [1], which applies very well to imaging the steep gradient region of H-mode edge plasmas, the phase fluctuation □ imparted on the reflected beam by the perturbed cutoff surface is proportional to the amplitude of the density fluctuations. The proportionality factor is set in part by the local density and magnetic field gradients near the cutoff layer. Large variations in amplitude are indicative of either a breakdown of the phase-screen model or poor imaging and corruption of the signal by scattered radiation. In figure 4, the I/Q distribution from a representative MIR channel at 62 GHz is plotted for select time windows over the course of a density ramp. All 48 channels are continuously monitored in this fashion for the duration of DIII-D discharges. Since the plasma major radius of the optical focal plane is set by the position of the quasi-optical lenses, its position remains relatively constant; although changes in plasma refraction do have an effect on the position of the focal plane, this dependence tends to be weak. During the timeframe plotted in figure 4, the density ramp moves the 62 GHz cutoff layer from R = 2.16 m to R = 2.19 m. A reasonable experimental estimate for the depth of field is twice this distance, 6 cm. From the Gaussian beam approximation, one can calculate the depth-of-field which is twice the Rayleigh range, z_R

$$2z_r = 2\pi w_o^2 / \lambda \qquad (2)$$

where w_o is the Gaussian beam waist (half the spot size diameter). With a vacuum wavelength of 4.8 mm (62 GHz) and a spot size of about 1.8 cm, the depth of field is 11 cm. The experimental value of 6 cm for the depth-of-field determined from the density ramp is smaller than the calculation. The disparity is attributed to imperfect phase matching of the transmitter beam on the cutoff surface and imperfect optical alignment which limit the range of density over which high quality data may be obtained. Within 1500 ms to 1900 ms, the best optical coupling is achieved, evidenced by the annularly shaped I/Q plots, and this time window presents the best opportunity for high-resolution images of density fluctuations, which are presented in the following section.

3.2. MHD spectra of fully noninductive ELMing H-mode with reversed B_t

The period between ELMs is particularly interesting because of a rich spectrum of MHD activity observed by multiple diagnostics. Figure 5 shows spectrograms produced from CO_2 interferometer [14], ECE radiometer [15], Mirnov coil [16], and MIR diagnostics for shot 154412. The interferometer spectrogram is obtained from the cross-power of midplane (horizontal) and so-called edge (vertical) chords, representing n_e fluctuations at the intersection of the horizontal and vertical chords on the midplane at R = 2.1 m. The ECE spectrum (representing T_e fluctuations) is the cross-power between two adjacent channels near the midplane, just inside the last-closed flux surface at R = 2.156 m and 2.182 m. The magnetic spectrum is the cross-power between two high-frequency Mirnov probes located 50 degrees above the midplane, and separated toroidally by 2.2 degrees, representing magnetic fluctuations near the outboard plasma edge. The MIR spectrogram is obtained from the auto-power of a single channel, located 5 cm above the midplane and < 1 cm inside the last-closed flux surface at R = 2.185 m, in the steep gradient region of the pedestal. The MIR spectrogram in figure 5(d) is similar to those measured by other channels of the array.

In comparing MIR to other systems, we find that it performs well as a density fluctuation diagnostic; features that are strong in the interferometer spectrum are also strong in the MIR spectrum. For example, upward sweeping modes [c.f. figure 5(a)] clearly seen on the interferometer are also observed with the MIR instrument. The mode at 70 kHz produces a prominent magnetic fluctuation [c.f. figure 5(c)] but is not strong from the perspective of ECE, interferometry, or MIR. It is suspected that this 70 kHz feature resides in the core and is not evident on ECE, interferometer, and MIR because the chosen channels produce signals that dominate in the edge. Each diagnostic detects a coherent fluctuation at 100 kHz, but MIR also readily finds the neighboring mode at 110 kHz [c.f. figure 5(d)], which is near the noise level in the other diagnostics. One possible explanation for the clear signature on MIR is its high sensitivity to small density perturbations and its highly-localized spatial measurement allow MIR to detect fluctuations that line-averaged measurements (such as interferometry) and external measurements (such as Mirnov coils) cannot.

3.3. 2D Imaging of edge-localized density fluctuations during inter-ELM periods

MIR, like ECE-Imaging, produces a local measurement so that 2D mode amplitude and phase structure may be reconstructed. During the times with optimal focusing (t = 1500 – 1900 ms), numerous inter-ELM modes are simultaneously imaged over the same plasma volume. Observed for several ELM periods, each ELM burst precedes a set of coherent modes that sweep upward in frequency (figure 6). The long vertical tick marks in the Figure indicate ELMs. Following each ELM, a set of at least three coherent modes appears. At their onset, their frequencies are 55, 65, and 75 kHz and they sweep up in frequency over time. A difference of approximately 10 kHz, corresponding to the Doppler shift between these modes, is maintained until they are no longer visible in the spectrogram. Spectral analysis with the MIR array (described below) indicates that the toroidal mode numbers are n = 3, 4, and 5. The mode amplitude peaks at a time corresponding to about 1/4th the ELM period, and then fades below the noise floor by 1/2 the ELM period.

Images of the n=3 mode are produced by Fourier transforming the measured fluctuation signal from each of the 48 MIR channels. The real part of the complex amplitude of the particular spectral component of interest is recorded for each channel and plotted on a two-dimensional spatial grid. Images of the 58 kHz fluctuation at 1864 ms are shown in figure 7. The series of panels on the right represent a time sequence of the density fluctuation measured by MIR (top) and temperature fluctuation measured by ECE-Imaging (bottom), where successive panels represent a time difference of 1.9 μs . For MIR, since the modulation of the quadrature signal in the complex plane is dominated by phase fluctuation at the time selected, the contours in figure 7 are proportional to the density fluctuation amplitude, $\tilde{n} / n$.

The left panel of figure 7 shows a portion of the EFIT equilibrium reconstruction constrained by the motional Stark effect (MSE) diagnostic [17,18]. The plasma region measured by MIR is determined by calculating the RX cutoffs for the four probe frequencies (62, 63, 67, and 68 GHz) using profile fits of the density and magnetic field. It is clear from the images that the fluctuation has a helical structure (i.e. it can be characterized by some finite poloidal and toroidal mode number). The 58 kHz mode captured in figure 7 has a poloidal variation with wavelength λ_θ = 30 cm, or poloidal wavenumber k_θ = 3.3 m^{-1}. The density fluctuations peak near the last closed flux surface, a region of steep density gradient, and decrease monotonically inward.

3.4. Mode propagation and velocity-space representation of MIR data

Its multi-dimensional measurements and high time resolution allows MIR to quantify dynamic properties of the density, namely local values of the apparent plasma rotation and phase velocity of fluctuations. Complementing the spectrograms (such as those in figures 5 and 6), velocity-space maps offer an extra dimension to the data; while spectrograms illustrate the power distribution in frequency and time, velocity-space maps reveal the power distribution in frequency and wavenumber, from which rotation and phase velocities can be inferred. The velocity-space maps are generated by cross-correlating the spectra of each pair of poloidally-separated channels. Values of the cross-power and cross-phase are calculated for each pair over the frequency range of interest. Wavenumbers are determined by dividing the cross-phase by the spatial separation of each channel pair. The ensemble of cross-power values produce an array for coupled power spectral density that are plotted versus two-sided frequency and wavenumber.

A time sequence of the density fluctuations in velocity space measured by MIR is generated and shown in figure 8. The data in each of the top four panels represent the cross-power of all poloidal channel pairs on the 63 GHz cutoff layer located in the steep gradient region of the pedestal. Both sides of the frequency spectra are plotted to accentuate the trends observed by MIR. Subtle asymmetries in the two-sided spectra are likely due to Doppler effects, a consequence of the MIR lines-of-sight intersecting the cutoff surface slightly off-normal.

By representing MIR data as in figure 8, the apparent phase velocities of waves constituting the density fluctuations can be determined by inspection, ω/k. Groups of modes are often observed that appear to be of the same branch of instability. They appear at distinct k and ω, but have a relationship suggesting that their relative difference frequency is dominantly produced by Doppler shift due to the rotation of the plasma reference frame, the ion fluid rotation, for example. If one assumes that Doppler shifts are much larger than other effects that may cause mode frequency to change as a function of k, then connecting the two modes with a line in frequency-k_θ space, defines a velocity which we will call the n-dependent velocity of the group,

$$v_g^{(n)} \equiv \frac{\Delta\omega/\Delta n}{\Delta k_\theta/\Delta n} \quad .$$

Because the total Doppler shift observed by MIR has components due to both toroidal and poloidal acceleration of the reference frame, this velocity constrains toroidal and poloidal flow, as well as the pitch angle of the mode, $\gamma = B_p/B_t$,

$$v_g = v_{pol} - \gamma v_{tor} \quad . \tag{3}$$

The natural frequency of the oscillation, ω_0, a valuable parameter for comparison to theory, is obtained by removing Doppler shift contributions at the limit $\omega(n \to 0)$, which is the intersection of this line with the k_θ=0 axis.

The time within the ELM period from which each velocity-space map is generated is indicated by a vertical dashed line on the spectrogram in figure 8. The spectrogram shows that appreciable power grows in at least three distinct high-frequency components (|f| ~ 55, 65, and 75 kHz) early in the ELM period. The 55 kHz and 65 kHz modes appear as the strongest in the first cross-spectral plot (frame A of figure 8), and it can be seen that they form a linear relationship with rotational group velocity, v_g of -16 km/s and f_0 = f(k = 0) = 24 kHz. The frequency f_0 corresponds to the real frequency of the mode in the rotating, plasma reference frame. By frame B, power grows in an additional semi-coherent mode (|f| ~ 40 kHz), and the three high-frequency modes seen in frame A persist, sweeping up slightly in frequency. A linear fit to the high-frequency set of modes in frame B yields v_g of -22 km/s with f_0 = 10 kHz, but the moderate-frequency fluctuation does not yet exhibit a clear dispersion. Midway through the ELM period, the high-frequency modes disappear, and power grows substantially in the moderate-frequency semi-coherent mode as well as a low-frequency broadband feature. Values of v_g and f_0 for the moderate-frequency mode in frame C are -11 km/s and 14 kHz, respectively. An event around 1810 ms modifies the measured dynamics of the semi-coherent mode. Following this event, as can be seen in frame D, the magnitude of the measured rotational group velocity of the mode increases (v_g = -15 km/s) while the real frequency of the mode decreases (f_0 = 5 kHz). These values persist until the onset of the next ELM. Some subjectivity is involved in fitting the low-frequency feature due to its broadband nature. Following the event around 1810 ms, the spectral characteristic of broadband feature tends to coalesce in phase space, allowing an opportunity for more accurate fitting. Calculations of v_g and f_0 for the broadband fluctuation in frame D are -5 km/s and 0 kHz, respectively. These results are summarized in Table 2.

Toroidal and poloidal plasma rotation is routinely measured on DIII-D with charge-exchange recombination (CER) spectroscopy [19,20]. CER is an active diagnostic requiring neutral beams to generate its signal. Unfortunately, during the time range of interest for MIR shown in Figure 8, the neutral beam used by the vertical CER system (from which poloidal rotation is inferred) was not available. Earlier in the discharge, however, the required neutral beam was on at a very low duty cycle. The last neutral beam pulse (t = 1480 ms) is aligned well with the middle of an ELM period, yielding carbon-ion toroidal rotation of 60 km/s (counter-clockwise viewed from above the tokamak) and carbon-ion poloidal rotation of +2 km/s (directed downward at the outer midplane) in the pedestal. From MSE-constrained EFIT equilibrium, the magnetic field pitch angle in the steep gradient region is approximately -0.1. Assuming the observed modes are approximately aligned with the field, from equation (3), we arrive at v_g = -4 km/s for a fluctuation traveling at the carbon-ion velocity. This estimated value is close to that calculated for the low-frequency broadband feature (-5 km/s) measured later in the discharge by MIR. Speculation on the relationship between the evolution of fluctuations and the poloidal rotation with implications toward ELM stability will be presented in future work.

4. Summary

The MIR system represents the current state-of-the-art in millimeter-wave plasma imaging technology, but several upgrades are planned for the near and long terms. In the near term, the 4-frequency up-converting probe source will be replaced with an 8-frequency source, with a longer term goal of 16 frequencies. This not only expands the number of pixels and coverage area but also provides the flexibility to arbitrarily position the coverage window radially. In the long term, shaping and focusing the MIR beams by large aperture lenses will be replaced by electronic beam forming [13]. This upgrade has several advantages: 1) smaller diagnostic footprint, 2) broader range of wavefront shaping and focusing, and 3) opportunity to dynamically shape, focus, and track during a discharge. The third point is particularly promising as it allows the possibility for a feedback control system to track the cutoff surface and to adjust the beam forming to continually provide plasma coupling through an entire discharge under even the most dynamic conditions.

During its first operational campaign on DIII-D, MIR measured a wide variety of fluctuation phenomena. For the discharge studied here, the main objective was to demonstrate the analysis capabilities possible with MIR data by characterizing fluctuations observed within an inter-ELM period. Its highly-sensitive, localized measurements of density fluctuations yield rich spectra that suggest a very active pedestal region between type-I ELM bursts. Two-dimensional images allow for visualization of the fluctuations as they would exist physically in the plasma, while velocity-space maps, coupled with temporally-resolved spectrograms, serve as a convenient visual representation for the evolution of MHD and turbulence in three-dimensional phase space: frequency, time, and wavenumber. From the evolution of fluctuations in such a representation, information can be drawn about their spectral content, dispersive nature, and rotation velocity. MIR provides an additional means from which to infer plasma quantities besides fluctuation information; since the apparent rotation velocity measured by MIR depends on three quantities (poloidal and toroidal rotation of the reference frame and the pitch angle of the fluctuation), given any two of these, the third can be determined from MIR measurements.

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Table 1. Typical MIR parameters

Poloidal coverage	~20 cm centered at midplane (dependent on cutoff shape)
Channels	12 poloidal x 4 radial
Tunable frequency range	56 – 74 GHz
Radial resolution	Better than 5 mm (dependent on density gradient)
Poloidal spot diameter	3.0 cm
Poloidal channel spacing	1.7 cm
Resolvable k_r	Up to 100 m^{-1}
Resolvable k_θ	Up to 30 m^{-1}
Resolvable n_e fluctuation	Up to 5%

Table 2. Summary of the values of the measured group velocity and natural frequency of the fluctuation from linear fits of 3 classes of modes present during the type-I ELM period. The lettered labels correspond to the time slices in figure 8.

		A	B	C	D
High-freq.	v	-16 km/s	-22 km/s	-	-
	f_o	24 kHz	10 kHz		
Moderate-freq.	v	-	-	-11 km/s	-15 km/s
	f_o			14 kHz	5 kHz
Low-freq.	v	-	-	-	-5 km/s
	f_o				0 kHz

Figure Captions

Fig. 1. Characteristic resonances and cutoffs for DIII-D H-mode discharge #154412. (a) 1D radial plot at the midplane (z = 0) showing the O-mode and right-hand RX cutoffs as well as the UH and electron cyclotron resonances. The frequency range (56 – 74 GHz) of MIR during the 2013 experimental campaign is denoted by the horizontal dashed lines. (b) 2D radial-poloidal plot. The UH resonance and RX cutoff for the center frequency (65 GHz) of MIR are plotted. The last-closed flux surface (LCFS) and the vessel wall are also shown.

Fig. 2. Inside the MIR detector array enclosure: mini-lens antennas [21] lie on a curved surface to produce a focal plane that matches the shape of the cutoff layer. Two staggered semi-arrays of six antennas each are in perpendicular planes. A large beamsplitter (not shown) inserted between the two semi-arrays distinguishes the local oscillator and signal paths for heterodyne detection.

Fig. 3. (a) Schematic showing the source frequency generation, down-conversion of the receiver signal, and IF signal processing throughout the mm-wave transmit, mm-wave receive, and IF down-conversion subsystems. (b) An overview of the physical system layout including the paths for transmitter and receiver power and local oscillator. (c) The mixed output at the detector array is passed to one of 12 IF modules where 4 transmit frequencies are discriminated and amplitude and phase are recorded.

Fig. 4. Average line-integrated electron density along the midplane measured by CO_2 interferometer and D_α time traces for t = 1000 – 2000 ms for DIII-D shot 154412. ELMs are identified as the sharp spikes in the $D\alpha$ signal. I/Q plots from a representative MIR

channel are plotted showing the evolution during the density ramp. The time window t = 1500 – 1900 ms produces the smallest amplitude modulation and best focusing.

Fig. 5. Spectrograms for DIII-D shot 154412 of (a) cross-power between radial and vertical interferometer chords (frequency sweeping mode activity is indicated), (b) cross-power between two ECE channels located just inside the last-closed flux surface, (c) cross-power between two high frequency magnetic coils located outside the plasma and near the midplane (core mode uniquely observed on magnetics is indicated), and (d) auto-power of a representative MIR channel (the 110 kHz mode uniquely observed on MIR is indicated). The region between the vertical dashed lines indicates times where the best focusing is achieved with MIR.

Fig. 6. MIR auto-spectrum of one representative channel showing three ELM bursts (denoted as vertical dashed lines) and the myriad of inter-ELM activity. The box encircles the 58 kHz mode at 1864 ms which is analyzed here.

Fig. 7. (a) Mapping of the two-dimensional coverage areas measured by MIR and ECE-Imaging onto a poloidal-radial cross-section of the DIII-D plasma. The smaller of the two boxes is the MIR window. The cutoff layers are calculated by the cold plasma dispersion relation including a relativistic correction to the electron mass. The cutoff layers corresponding to the highest and lowest MIR probe frequencies used for this particular discharge are overplotted, as well as the LCFS. (b) Time sequence of the 58 kHz density fluctuation at 1864 ms measured by MIR (top) and temperature fluctuation measured by ECE-Imaging (bottom). The size of the panels is scaled to preserve the vertical-to-radial ratio of the measurement window.

Fig. 8. Velocity-space evolution of density fluctuations measured by MIR in the pedestal during an ELM period. The top sequence of plots represents cross-spectral power versus frequency and poloidal wavenumber. One ELM period is represented in the spectrogram; the ELMs are identified as the broadband bursts at approximately 1760 ms and 1840 ms. The time within the ELM period from which each cross-spectral plot was generated is indicated by a vertical dashed line overlaid on the spectrogram.