Multi-dimensional Visualization of Turbulence in Fusion Plasmas

Christopher M. Muscatello, Calvin W. Domier, Xing Hu, Neville C. Luhmann Jr., Xiaoxin Ren, Paul Riemenschneider, Alexander Spear, Liubing Yu
University of California, Davis

Benjamin J. Tobias
Princeton Plasma Physics Laboratory

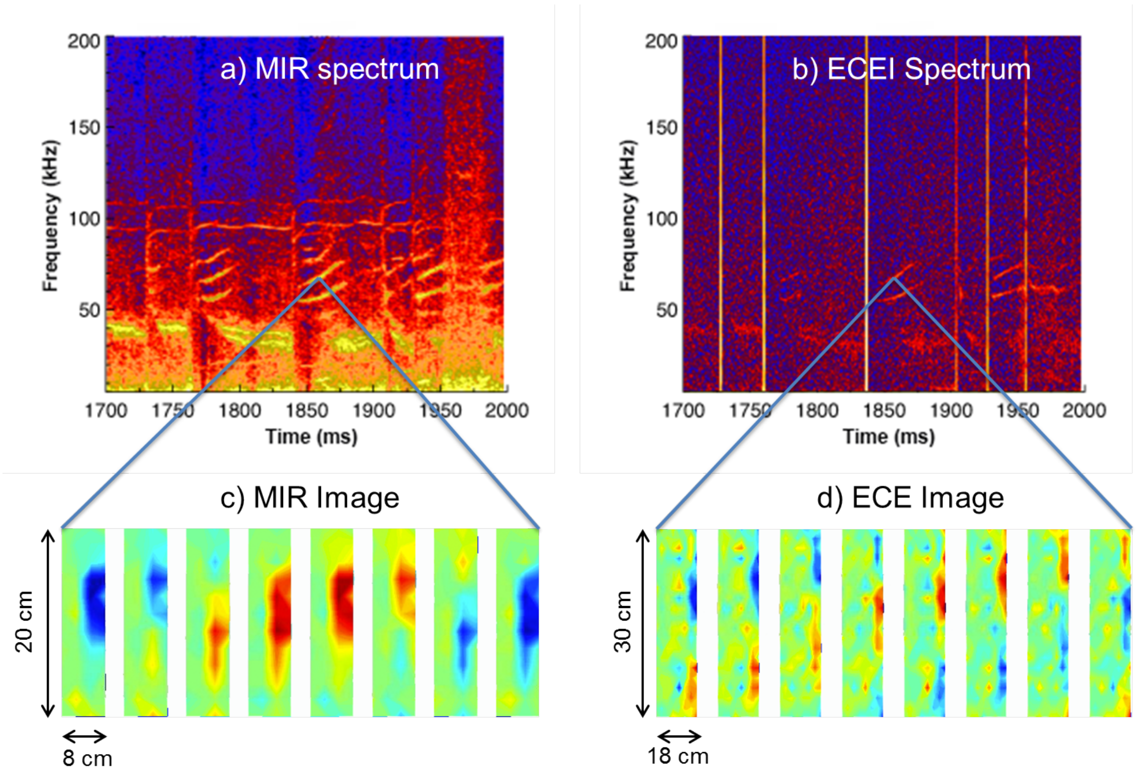

Fig. 1. Images of electron density and temperature fluctuations inside a tokamak fusion plasma. The top two plots are spectra of representative channels from a) MIR and b) ECEI showing fluctuations during edge-localized mode activity. The bottom two plots are c) density and d) temperature image reconstructions of the 66 kHz fluctuation at 1860 ms.

***Abstract* – Quasi-optical imaging at sub-THz frequencies has had a major impact on fusion plasma diagnostics. Mm-wave imaging reflectometry utilizes microwaves to actively probe fusion plasmas, inferring the local properties of electron density fluctuations. Electron cyclotron emission imaging is a multi-channel radiometer that passively measures the spontaneous emission of microwaves from the plasma to infer local properties of electron temperature fluctuations. These imaging diagnostics work together to diagnose the characteristics of turbulence. Important quantities such as amplitude and wavenumber of coherent fluctuations, correlation lengths and decorrelation times of turbulence, and poloidal flow velocity of the plasma are readily inferred.**

Thorough diagnosis of fusion plasma fluctuations leads to a better understanding of conditions that achieve good performance. Reflectometery is an active, radar-like diagnostic frequently employed to non-perturbatively probe the density of fusion plasmas. Mm-wave imaging reflectometry (MIR) probes the plasma with multiple, simultaneous frequencies, producing a 2D image of electron density fluctuations. Where densities are appreciable, tokamak fusion plasmas are good blackbody radiators. Therefore, in the majority of the plasma, the electron cyclotron emission (microwave range of frequencies) from the plasma depends only on the electron temperature.

Electron cyclotron emission imaging (ECEI) measures this radiation for multiple frequencies, producing 2D images of electron temperature. Providing spatiotemporal-resolved pictures of turbulence and magnetohydrodynamic eigenmodes, mm-wave imaging diagnostics allow for analysis of radial and poloidal correlation lengths, fluctuation wavenumbers, and both the phase and group velocity of propagating modes.

ECEI is an extension of the traditional single-chord radiometer, employing multiple spatially-separated sightlines [1]. The detectors are broadband, capable of simultaneously measuring multiple frequencies, enabling the system to generate a 2D array of temperature fluctuations.

Imaging reflectometry was originally conceived to address concerns where conventional reflectometry falls short, namely issues with mm-wave coupling of the probe and reflected signals into and out of the plasma [1,2]. Without imaging the reflected radiation, data is often no more meaningful than scattered glare. When radiation is properly imaged, a picture, as the eye would see, emerges. The implementation of MIR on the DIII-D tokamak advances these principles by incorporating multiple probe frequencies and spatially-separated sightlines to generate a 2D array of density fluctuations. It is the first to employ a non-planar imaging array where the antenna detectors lie on an arch of a circle, which produces a focal plane in the plasma that closely matches that of the cutoff. The result is a highly sensitive mm-wave camera that produces unprecedented images of density perturbations with robustness and clarity.

Individually, MIR and ECEI provide spectral and structural information about turbulence. The combined MIR and ECEI system on DIII-D (simultaneously measuring n_e and T_e fluctuations of the same plasma region) provides the capability to infer coherence and phase relations between the two fundamental plasma properties.

In tokamaks, the so-called “high confinement” or H-mode regime is a promising scenario for steady-state operation, as sought for a commercial reactor. H-mode plasmas are characterized has having a prominent edge transport barrier or “pedestal,” evident as local maxima in electron density and temperature. However, periodic bursts of energy, particles, and momentum associated with edge-localized modes (ELMs) frequently plague H-mode plasmas, limiting the height of the pedestal and leading to increased edge transport. A clear understanding of the mechanisms leading to an ELM burst would help to refine or devise ELM avoidance and suppression schemes. A myriad of spectral features can be observed on fluctuation diagnostics during ELM activity. Example spectrograms from MIR and ECEI during several ELM bursts are shown in Figures 1(a) and 1(b). The broadband, short bursts are ELMs, and the frequency-localized spectral features suggest that edge stability is poor. Careful diagnosis of these coherent modes provides a means to benchmark theoretical models, which serve to ultimately provide insight into the causality of ELM onset.

Characterizing the physical structure of turbulence is less ambiguous when the measurement is made in multiple dimensions. In this regard, MIR and ECEI excel. Figures 1(c) and 1(d) are two-dimensional image reconstructions of the density and temperature fluctuation for the mode at t = 1860 ms and f = 66 kHz. The images are generated by Fourier transforming the raw signals and recording the amplitude of the spectrum for a particular frequency component. The images are contour plots of these values for the array ensemble. For this particular discharge and time, the ECEI window covers approximately 30 cm poloidally and 18 cm radially, while MIR covers approximately 20 cm poloidally and 8 cm radially. The arrays overlap and are centered on the midplane at the far edge of the plasma on the low-field side. The fluctuation has a periodic poloidal structure (vertical direction in the image) and it appears to peak near the last closed flux surface (far right side of the image). Each frame represents a phase shift of the periodic fluctuation (from 0 to 2π). The sequence of frames can be thought of as freezing the plasma in time and rotating the fluctuation passed the viewing window. Calculation of the cross-phase between neighboring pixels reveals the poloidal wavelength and wavenumber of the mode (λ = 30 cm, k = 0.2 cm^{-1}). The low wavenumber and the peaking of the mode amplitude at the plasma edge are suggestive of a ballooning-type instability where a ripple or periodic ballooning of the plasma occurs.
Of course MIR and ECEI extend well beyond imaging ELM-related events. During its first year of commissioning, the DIII-D MIR system observed a multitude of activity such as the edge harmonic oscillator (EHO) in quiescent H-mode plasmas and edge density perturbations associated with core tearing modes. ECEI’s ability to robustly image deep into the plasma makes it a unique diagnostic for measuring the structure of core activity such as Alfvén eigenmodes [3], tearing modes [4], and sawtooth oscillations [5].

This work was supported by the U.S. DOE under DE-AC02-09CH11466, DE-FG02-99ER54531 and DE-FC02-04ER54698.

REFERENCES

[1] B. Tobias *et al.*, Plasma and Fusion Research 6 2106042 (2011).
[2] E. Mazzucato, *et al.*, Phys. Plasmas **9** 1955-1961 (2002).
[3] B.J. Tobias *et al*., Phys. Rev. Lett. **106** 075003 (2011).
[4] I.G.J. Classen *et al*., Phys. Rev. Lett. **98** 035001 (2007).
[5] T. Munsat *et al*., Nucl. Fusion **47** L31 (2007).