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ECE-imaging of the H-mode pedestal (invited)\textsuperscript{a)}

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A synthetic diagnostic has been developed that reproduces the highly structured electron cyclotron emission (ECE) spectrum radiated from the edge region of H-mode discharges. The modeled dependence on local perturbations of the equilibrium plasma pressure allows for interpretation of ECE data for diagnosis of local quantities. Forward modeling of the diagnostic response in this region allows for improved mapping of the observed fluctuations to flux surfaces within the plasma, allowing for the poloidal mode number of coherent structures to be resolved. In addition, other spectral features that are dependent on both $T_e$ and $n_e$ contain information about pedestal structure and the electron energy distribution of localized phenomena, such as edge filaments arising during edge-localized mode (ELM) activity. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4733742]

I. INTRODUCTION

Spatial profiles of the H-mode pedestal have long been thought to be beyond the capability of ECE diagnostics, whose spatial resolution is limited by the finite bandwidth of their detection channels.\textsuperscript{1} Furthermore, since the emission is not guaranteed to be optically thick, interpretation is complicated by the presence of information about both $T_e$ and $n_e$.\textsuperscript{2–4} ECE-imaging (ECEI) places measurements at many more minor radii by forming a 2D array of measurements that are finely spaced radially and vertically about flux surfaces in the plasma edge. We show that modeling the diagnostic response to perturbations in this region allows ECE data to be used for quantitative diagnosis of the H-mode pedestal and edge localized phenomena.

The complicated nature of ECE in the edge region is exemplified by the longstanding observation of an anomalous feature in the ECE spectra measured by calibrated diagnostics, such as Michelson interferometers, grating polychromators, and heterodyne radiometers. This feature, shown in the ECE profile of Fig. 1, is manifest as a bump, or region of enhanced radiation temperature, $T_{\text{rad}}$, at frequencies corresponding to cold resonances [located in terms of the spatially varying magnetic field by $f = 56 \cdot B_T(\text{GHz/T})$] outside the last closed flux surface of the plasma. The feature is non-physical, and cannot be corroborated by Thomson scattering or Langmuir probe data. This bump is reminiscent of an intense, non-thermal feature reported on TFTR,\textsuperscript{5} but occurs on DIII-D for pedestal electron temperatures on the order of 1 keV. With the observation of this feature in JET plasmas, it was hypothesized that various mechanisms, such as scattering of fundamental harmonic, ordinary mode emission, could be responsible.\textsuperscript{6} In this paper, we show that this anomalous emission, at frequencies below the cold resonance of the second harmonic extraordinary mode at the plasma edge, is accounted for by a simple model that invokes only isotropic, singly Maxwellian electron distributions in thermal equilibrium. Anomalous features are shown to be the result of inhomogeneities in $T_e$ and $n_e$, inherent to independently corroborated profiles of the H-mode pedestal.

Section II describes in detail how the ECE spectrum is calculated and addresses the simplifying assumptions that are made. The simulated emission spectrum is presented, and the mechanisms that produce anomalous emission are described. Consequences for the interpretation of ECE fluctuation diagnostics and ECE-imaging are discussed in Sec. III. In Secs. IV and V, modeling of the emission

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Calibrated ECE radiometry data, DIII-D shot #146060, $t = 1180.2$ ms, reproduces the $T_e$ profile over a broad range of frequencies corresponding to radial locations inside the optically thick region of the plasma. However, an anomalously high radiation temperature is observed at 88.5 GHz, corresponding to a position outside the plasma edge. This feature is non-physical and not corroborated by other diagnostics.}
\end{figure}
II. MODELING OF THE EMISSION SPECTRUM

Much of the description of emission processes, particularly in low-density regions of the plasma, relies on evaluation of a single-valued local quantity: the optical thickness, \( \tau = \int_0^\infty \alpha \, ds \), where \( \alpha \) is the absorption coefficient. Estimation of \( \tau \) by evaluation of the local approximation (cf. Table IV of Ref. 3) is routinely performed for differentiation of optically thick and optically thin regimes, but requires that \( T_e \) and \( n_e \) gradient scale lengths be significantly larger than the region over which \( \alpha \) must be integrated for adequate convergence of \( \exp[-\tau] \). This condition is violated in the region of the H-mode pedestal, however, and the total emission intensity coupled to the diagnostic along a direct line of sight, \( s \), must be calculated at each frequency, \( f \), and at each location, \( x \), by numerical evaluation of,

\[
I(f, x) = T_e(x) \alpha(f, x) \exp[-f \alpha(f, x) ds]. \tag{1}
\]

If the frequency response of the diagnostic is known, then this emission intensity profile may be integrated over the bandwidth of the diagnostic and again along the line of sight to give the total diagnostic response. Doppler and relativistic spreading of discrete frequencies is accounted for in the corresponding absorption coefficient profiles, which are evaluated following the prescriptions of Ref. 3. Integration along scattered and reflected paths is not performed since these corrections are small for the conditions of interest, where scattering at internal plasma cutoff surfaces and absorption at other resonances dominate over wall refractions.

By integrating the local emission intensity, \( I(f, x) \), over frequency, \( f \), the spatial profile of emission intensity contributing to signal in each diagnostic channel may be plotted. The bandpass characteristics of 8 midplane channels of the ECE-imaging diagnostic\(^7\) are used. This analysis reveals the source of the radiation along with the resolution of individual diagnostic channels, and is shown in Fig. 2 for a generalized example of a DIII-D H-mode discharge.

Channels with center frequencies resonant well inside the plasma edge, where the emission is considered to be optically thick, have integrated emission intensities which may be calibrated to the electron temperature profile and respond linearly to local temperature fluctuations. The diagnostic response to channels with cold resonances outside the steep gradient region, however, is not well described by a local approximation. The bulk of the emission observed in these channels is relativistically downshifted emission that has not been reabsorbed and originates not in the scrape-off layer (SOL), but inside the steep gradient region. Therefore, it may have no direct correlation to the local plasma temperature near the cold resonance location.

A measurement of the radiation temperature profile, as it would be observed by an absolutely calibrated ECEI system, is simulated by scanning the center frequency of a single channel and at each step integrating \( I(f, x) \) in both frequency and space. Because it includes points taken from 20 separate lines of sight, finely spaced in minor radius, the resulting synthetic diagnostic \( T_{rad} \) profile, shown in Fig. 3, has a better resolution than either the absolutely calibrated heterodyne radiometer or the Michelson interferometer at DIII-D and reproduces the qualitative features of the anomalous emission observed by both of these profile diagnostics when the result is mapped to real space by using the conventional cold resonance mapping technique. \( T_{rad} \) for the bump is \( \sim 80\% \) of \( T_e \) at the pedestal top, and is in this case separated from the optically thick region of the measurement by 1.2 GHz. In practice, however, ECEI is not absolutely calibrated and this profile is not reconstructed directly during experiments. Rather, the features of this profile lend insight for the interpretation of fluctuation measurements.

III. DYNAMICS OF THE DIAGNOSTIC RESPONSE

Lacking absolute calibration, ECE-imaging is inherently a dc coupled fluctuation diagnostic. Making use of ECEI data

FIG. 2. The spatial profiles of emission arriving at the 8 midplane channels of the ECEI diagnostic are shown along with the generalized DIII-D H-mode \( T_e \) and \( n_e \) profiles used to generate this example. The origin of this emission deviates significantly from the cold resonance position (arrows at top) when the center frequency of the diagnostic channel has a cold resonance outside the steep gradient region, as is the case for channels 1 and 2.

FIG. 3. A simulated ECE spectrum is obtained by scanning the frequency of the synthetic diagnostic. The mapping of \( f_{ECE} \) to \( \rho \) is performed by evaluation of the cold resonance location, revealing a non-physical feature outside the pedestal akin to that observed in experiments.
to diagnose perturbations in $T_e$ and $n_e$, or infer underlying profiles requires a thorough understanding of the diagnostic response to profile perturbations. This response is sensitive to the height and width of the pedestal, as well as its position relative to the cold resonances of the diagnostic frequencies. Inspection of emission and absorption terms calculated for discrete frequencies near the cold resonance of the last closed flux surface (LCFS) reveals 3 regimes of diagnostic response (cf. Fig. 4): a) optically thick, black body emission, b) optically grey emission producing a diagnostic response anti-correlated to changes in $T_e$ near the origin of the emission, and c) optically thin emission originating from the tail of the broadened emissivity profile.

ECE emission originating from a single location is broadened in frequency, and in tokamak geometry the origin of emission at a given frequency is broadened in space. Even for $T_e$ of ~1 keV, relativistic broadening is the dominant mechanism affecting the spatial profile of the absorption coefficient at fixed frequency and has the effect of shifting the peak of the resonance toward higher magnetic field. This produces a tail extending to smaller major radii. Under optically thick conditions, this tail is reabsorbed, allowing only the resonant plasma layer nearest to the observer to produce detectable emission. Hence, black-body emission, for which $T_{rad}$ is linearly proportional to $T_e$ near the cold resonance position, is often termed “last layer” emission [cf. Fig. 4(a)].

When the cold resonance is located in a region of low $T_e$, the absorption coefficient profile may be extremely narrow. Total absorption, which is a spatial integral of this quantity, is small. Emissivity in this region is also small when $T_e$ is low, but if there is a region of warmer plasma nearby, its emission will be broadened to include these frequencies. This downshifted emission constitutes nearly all of the signals detected by ECEI for the frequencies modeled in Figs. 4(b) and 4(c), but the diagnostic response in these two cases is very different.

The absorption coefficient, $\alpha$, appears as a coefficient in the local emissivity, $j(\omega, x) = T_e(x)\alpha(\omega, x)$, as well as an integrand in the reabsorption term, $\exp[-\tau]$, resulting in competition between emission (a local effect) and absorption (a non-local, line integrated effect). The narrow, steep gradient region of the H-mode pedestal generally has a much narrower spatial extent than that of the absorption coefficient profile for a given discrete frequency, let alone the range of frequencies that may be within a single diagnostic channel passband. Therefore, there exists a regime of diagnostic response for which a rigid displacement of the equilibrium pressure profile produces a signal dominated by changes in optical thickness rather than emissivity [cf. Fig. 4(b)]. This regime responds in an anti-correlated fashion to plasma displacements. When the plasma edge is shifted outward (inward), temperature and density everywhere increase (decrease), but not uniformly. If the region of greatest absolute increase (decrease) is properly positioned with respect to the absorption coefficient profile, then detected emission decreases (increases). This behavior has been observed repeatedly and reliably in ECE and ECEI data obtained during MHD activity that perturbs the location or structure of the plasma edge, and accounts for the narrow region of low radiation temperature, which separates regions of optically thick and optically thin emission spectra.

With the steep gradient region centered well into the relativistically broadened emission tail, sufficiently far from the cold resonance [cf. Fig. 4(c)], local contributions to the emissivity dominate and the dynamic response of the emission is again in phase with the perturbation. The response is no longer linear, however, and an absolute calibration is no longer possible. The intensity of observed emission is sensitive to changes along the line of sight, and the amplitude of the diagnostic response to perturbations inside the pedestal may be modified by changes to pedestal and SOL profiles.

**IV. POLOIDAL MODE STRUCTURE OF EDGE PERTURBATIONS**

Identifying a regime in which the emission spectrum is effectively black-body allows one to confidently diagnose the poloidal structure of temperature perturbations within the corresponding region of the plasma. Spatial profiles revealing the origin of observed emission, such as those shown in Fig. 2, may be used to accurately map an experimentally measured diagnostic response to flux surfaces. The synthetic diagnostic is also used to verify that the channels used are not sensitive to fluctuations in temperature and density elsewhere along the line of sight.

The edge harmonic oscillation (EHO) is a spontaneous edge fluctuation arising in QH-mode plasmas, and is thought to provide particle transport responsible for the suppression of...
ELMs in this operating regime.\textsuperscript{8–11} Validation of theoretical models for this instability is naturally a subject of great interest since it may some day enable ELM free, high performance operation in ITER and beyond, particularly if a similar mode may be excited under a broader range of conditions, such as low injected torque and lower rotational shear.\textsuperscript{12} Diagnosing the structure of this mode is further motivated by recognizing that methods developed for this purpose find immediate application in diagnosing the plasma response to other applied non-axisymmetric fields, such as resonant magnetic perturbations (RMP) for the suppression of ELMs.\textsuperscript{13, 14}

The diagnosis of coherent poloidal structure begins with taking a Fourier transform of all ECEI signals and identifying a Fourier window that represents the coherent MHD of interest.\textsuperscript{15} The spatial structure of the mode is represented in real and imaginary parts, or cosine and sine transforms, respectively. An example is given in Fig. 5, where the fundamental harmonic of an $n = 1$ EHO appearing in ECEI spectrograms has been selected for analysis. The ECEI detection bandwidth, in this case 78.05–85.15 GHz over 8 channels, each with 700 MHz resolution, spans frequencies both above and below the cold resonance of the LCFS.

Channels with an optically thick diagnostic response have been remapped from their respective cold resonance positions to closed flux surfaces inside the plasma. This is done by calculating the mean radius of the emission source from profiles such as those shown in Fig. 2. The diagnostic responses in both the anti-correlated and optically thin regimes are visible, but because the position from which their emission originates is not generally unique, they remain mapped to their cold resonance locations, producing a banded structure of alternating positive and negative responses in $\delta T_{rad}$. This structure is routinely observed and known to be characteristic of a rigid shift or unidirectional displacement of the flux surfaces. Only optically thick channels will be used to diagnose the poloidal mode structure as they reflect local quantities in a region where the straight field line poloidal angle, $\theta$, is well defined.

Optically thick ECEI measurements produce a 2D array of data points that may be interpolated to provide the amplitude and phase of oscillations in a native coordinate system, namely, a straight-field line coordinate system,\textsuperscript{16} where the streaming function, $v$, modifies the poloidal angle, $\theta$, such that when following the path $ds = d\phi d\theta$, one remains on a magnetic field line of the plasma equilibrium. Data from the region within the view of the ECEI diagnostic is then fit to basis functions of $\exp[im(\theta + \phi)]$, which extend on each flux surface around the poloidal cross-section, $\zeta = \zeta_0$. At each increment in minor radii, a best poloidal mode number is selected, representing the dominant poloidal mode structure vs $\rho$. Poloidal mode number, $m$, is not restricted to integer values, as theory predicts the EHO to be ballooning, and at many radii a superposition of closely spaced integer mode numbers. Each of these superpositions is represented in the poloidal decomposition of ECEI data as a single non-integer $m$-number, the mean of the constituent integer modes. The technique has been benchmarked by synthetic diagnosis of edge localized, periodic mode structures of low to moderate $n$-number obtained in the GATO (Ref. 17) and ELITE (Refs. 18 and 19) codes, demonstrating the resolution and robustness necessary to diagnose the effective poloidal structure of EHOs observed during QH-mode operation on DIII-D.

The poloidal mode structure of the EHO may be reconstructed over a complete poloidal cross-section by this method, and this has been done for several QH-mode discharges at DIII-D. With the toroidal mode number, $n$, diagnosed with data from the magnetic probe array,\textsuperscript{20} it is found that, in general, the winding number of the mode, $mn$, is greater than and not resonant with the $q$ profile in the region that may be diagnosed with ECEI ($\rho \sim 0.7–0.95$). Rather, the helicity of the mode structure is approximately equal to some multiple of the $q$ profile. An example of this result, taken from shot #146471 at $t = 1.356$ s, is given in Fig. 6. Although the EHO in this case is predominantly $n = 1$, the poloidal structure at the fundamental EHO frequency is characterized by $m \sim 4q$.

V. FILAMENTS COINCIDENCE WITH TYPE-I ELMs

In contrast to coherent, periodic fluctuations such as the EHO, there are many dynamic phenomena associated with ELM activity that are not well described exclusively by the optically thick emission that is available. The interpretation of ECE-images of these events represents the greatest challenge to the diagnostician. A unique inversion of ECE-images may not be possible in all cases, but forward modeling with synthetic diagnostics plays a key role in making use of this data for comparison to theory. Of particular interest is the identification of certain characteristic responses that are indicative of narrowly defined behaviors. These simplified cases are useful in that they help to guide data interpretation in its earliest

![Image](https://via.placeholder.com/150)
FIG. 6. ECEI data imaging an $n = 1$ EHO (shot #146471, $t = 1.356$ s) is used to diagnose the dominant poloidal mode number of the perturbation. The 2D mode structure in the poloidal plane (a) is obtained by fitting a set of quasi-periodic basis functions in a straight field line coordinate system to ECEI measurements from the overlaid box at the outboard side. Mode numbers are fitted in the region $0.75 < \rho < 0.95$ (b). The effective $m$-number is plotted as a function of $\rho$ in this range (c).

FIG. 7. A filament of constant density and temperature is modeled and a signature ECEI response is produced. Radial locations of the filaments are shown in (a), with the corresponding ECE-images in (b), $\delta T_{\text{rad}}/(T_{\text{rad}})$ (au). Of note are the false image outside the LCFS appearing at time (I), and the anti-correlated response that is produced when the filament traverses the steep gradient region of the pedestal at time (II).

stages, leading to the most informed evaluation possible given a limited or incompletely constrained perspective.

One such “signature” has been observed in attempting to synthesize ECEI data using a model proposed for the behavior of filaments observed during ELM activity. Spatially localized, current carrying structures have been observed on several tokamaks at the time of ELM crashes. The simplest model for the formation of a filament and its ejection from the plasma requires only a poloidally localized structure of constant electron density, with electron energy above the level of the background equilibrium plasma, translating across the edge plasma and into the SOL. A perturbation of this type is shown in Fig. 7, along with the simulated ECEI response, as it traverses the plasma boundary. The filament in this case has a peak density of $0.3 \times 10^{19}$ m$^{-3}$ and perturbs the locally Maxwellian energy distribution by 10%. Equilibrium profiles are taken from DIII-D shot #145049, and the simulation is representative of a wide range of H-mode discharges with pedestals not in ECE cutoff.

While the perturbation is inside the pedestal but near the steep gradient region, the ECE-image shows a perturbation to radiation temperature at two frequencies, corresponding to positions inside and outside the LCFS [cf. Fig. 7(b)]. The image inside the LCFS is the “true” image: a linear response to the local perturbation of optically thick plasma. The image mapped outside the LCFS is a “false” image and is composed of downshifted emission not well reabsorbed due to the sudden drop off in $n_e$ at the plasma edge. This false image may actually appear larger than the true image, depending on the characteristics of the SOL plasma.

As the perturbation passes through the steep gradient region, ECE-images show two closely spaced, in-phase responses, with a third, anti-correlated response near the LCFS frequency [cf. Fig. 7(c)]. This is reminiscent of the banded structure shown in Fig. 5, and similarly accounted for by a competition between $\tau$ and $j$, both of which are functions of the absorption coefficient profile and contribute to the observed emission intensity in the optically grey regime. The precise location and intensity of the anti-correlated response may be predicted by inspection of the equilibrium ECE spectrum produced by the synthetic diagnostic. It corresponds to the region of inverted gradient in the curve of $T_{\text{rad}}$ vs $f_{\text{ECE}}$.

Once the filament has passed completely into the SOL, its presence no longer affects signals corresponding to optically thick regions of the plasma identified earlier [cf. Fig. 7(d)]. The response is now either (a) local and representative of the filament itself or (b) non-local and purely representative of changes in the absorption of downshifted emission originating inside the LCFS. These two cases are differentiated by the density of the filament, with denser filaments, such as the case shown, corresponding to the former description.
The synthetic diagnostic is also capable of simulating the response to a bi-Maxwellian temperature distribution, where a population of suprathermal electrons, such as may be present in the formation of a runaway electron beam, is introduced as a poloidally localized structure. Filaments with fixed \( n_e \) of a few percent and \( T_e \) 10–100 times values at the pedestal top have been simulated. It has been confirmed that suprathermal populations are only observable by ECEI when they produce a significant amount of radiation within the narrow band of poorly reabsorbed frequencies represented by the anomalous bump in the equilibrium ECE spectrum. In contrast to purely thermal perturbations, they do not produce a true image. Nor do they produce an anti-correlated signature when localized near the LCFS.

Filaments imaged by ECEI likely express attributes that are somewhere in between the two limiting cases modeled above. In Fig. 8, an example of an ELM filament occurring during shot #146397 at \( t = 2.247 \) s is imaged in three frames spanning only 6 \( \mu \)s. The signature of a thermal population crossing the LCFS is clearly observed, and the ECE-image supports the hypothesis that this filament is ejected from the pedestal and passes into the SOL. The intensity of the emission due to the filament is more than 15 times greater than the background, however, and no conclusive estimate for absolute local quantities has been made. This is the subject of ongoing work, and requires additional assumptions or constraints that may not be available from ECEI data alone, such as independent measurement of perturbed \( n_e \) or ECE measurements at oblique or tangential views.

VI. CONCLUSION

A synthetic ECE diagnostic applied to the pedestal of H-mode plasmas accounts for long-standing discrepancies between the ECE spectrum and \( T_e \) profiles obtained by other diagnostic techniques. Analysis of forward modeling shows that this narrow region of the edge plasma, often beyond the spatial resolution of standard techniques, produces a broadened ECE spectrum that is well within the frequency resolution of modern systems. For the cases shown, a region of the plasma edge \( \sim 2.5 \) cm in radial extent produces a unique diagnostic response in each of 3 ECEI channels at 900 MHz spacing. On DIII-D, this is repeated along each of 20 diagnostic lines of sight, leading to complicated structure in ECE profiles and ECE-images. Interpretation of this structure and measured fluctuations for the inference of plasma profiles and perturbations in this region represents a novel and powerful diagnostic technique.

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