Intense Millimeter Wave Radiation from the H-mode Pedestal in DIII-D at ITER Relevant Collisionality

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Brief periods of intense radiation at frequencies corresponding to the second harmonic of cold electron cyclotron resonances near the plasma edge have been observed in H-mode discharges on DIII-D [1]. These bursts in millimeter wave emission accompany type-I ELMs and have been characterized at ITER relevant collisionality ($\nu_e^* \leq 0.15$) [2]. Peak radiation temperatures above 100 keV are observed for durations of 5–10 μs. The emission is localized poloidally, and the observed frequency spectrum of an individual burst has a linewidth of less than 900 MHz, appearing in only one frequency channel of either the fast ECE radiometer [3] or the ECE-Imaging [4] diagnostic at a given time. The intense, localized emission cannot be accounted for by incoherent cyclotron radiation, and represents radiation by other mechanisms that are not yet fully understood but have important consequences for millimeter wave diagnostics on present and future fusion devices.

Signals acquired by the ECE-I diagnostic on DIII-D are presented in Fig. 1. Intense spikes of radiation are observed throughout the duration of ELM-associated MHD activity, often saturating the diagnostic at more than 100 times the radiation temperature of the background plasma. These bursts of radiation begin at the earliest onset of magnetic perturbations, approximately 100 μs before the rise in D_α emission detected by filterscopes viewing the divertor, and continue for another 100 μs afterwards. 2D images show the vertical localization of individual radiation spikes as determined by the orientation of the ECE-I detectors and imaging optics, as well as their frequency in relation to the second harmonic of cold plasma cyclotron resonances near the plasma edge. Spikes in emission appear at frequencies both above and below the cold-resonance of the LCFS, and may vary in frequency by several gigahertz over the duration of a single burst.

The most intense spikes appear in a region ±10 cm about the equatorial plane, but may also be observed at the extreme vertical extent of the ECE-I view, which is ±25 cm for the case shown. The origin of emission varies chaotically close to the ELM time, with multiple structures simultaneously appearing to propagate in both co and counter directions with respect to the observed rotation of the core plasma in the laboratory frame. The earliest structures observed at each event tend to rotate in the normal sense of plasma rotation, while structures appearing immediately after the crash are more likely to stagnate or propagate in the opposite direction. This may be associated with changes in plasma rotation near the edge correlated with modifications of the radial electric field at the crash time [5,6].

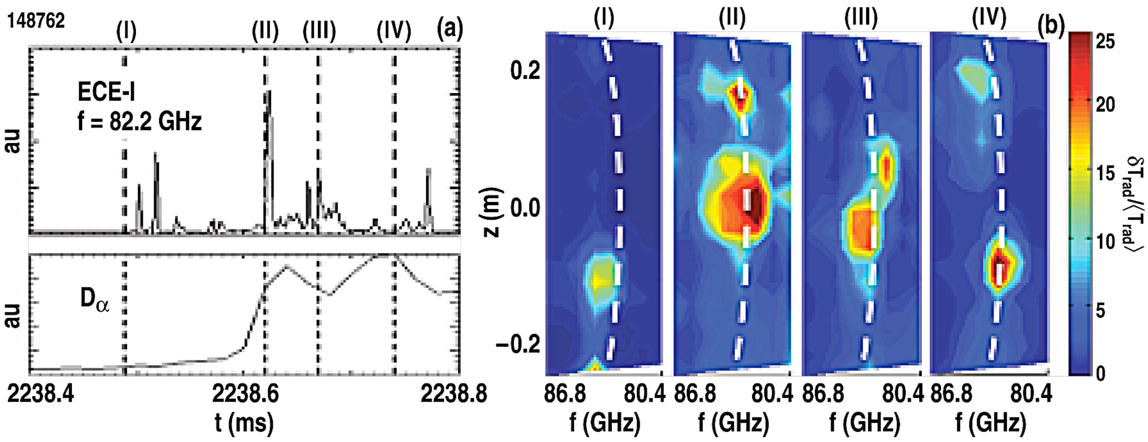

Fig. 1. Localized mm-wave bursts are imaged during shot 148762. (a) Signal from a single ECE-I channel at the midplane (top) is compared to filterscope measurement at the divertor (bottom), showing that bursts in emission begin approximately 100 μs before the ELM time. (b) At the times indicated, multiple sources of poloidally localized emission radiate at frequencies near the second harmonic of the cold plasma ECE resonance of the LCFS (dashed white line). Due to their localization, not all of these bursts appear in the time trace shown in (a).

Forward modeling of the expected diagnostic response has been performed for perturbations to the thermal electron population, as well as for bi-Maxwellian populations with a significant fraction of energetic tail electrons. This superposition of isotropic, Maxwellian electron populations in local thermal equilibrium [7–9] is used to explore the hypothesis that incoherent cyclotron radiation from a runaway electron tail may be responsible for the observed emission, even though there is no strong evidence of runaway electrons, such as hard x-ray emission. As reported in Ref. [7], steep gradients in electron density, temperature, and rapid variation in optical thickness of the cold-resonant frequency associated with the formation of a pressure pedestal in H-mode plasmas, allows ECE diagnostics viewing the plasma edge perpendicular to the magnetic field near the midplane to detect downshifted emission from energetic electrons inside the LCFS. This radiation is poorly reabsorbed by the tenuous plasma of the SOL, providing a window of frequencies over which a portion of the energy distribution of electrons in the pedestal may be diagnosed. However, as shown in Fig. 2, incoherent radiation of this kind cannot account for the exceptionally high radiation temperatures observed. As the energy of the fixed density

($0.1 x 10^{19}\ m^{-3}$) electron tail population is increased from 0 to 100 keV, the radiation temperature that would be observed by ECE-I is predicted to peak at 3.4 keV before again decreasing. This phenomenon may be attributed in part to the frequency of peak emissivity for increasingly relativistic electrons decreasing below the window of weakly reabsorbed emission, bounded at its lower limit by the right-hand cutoff frequency.

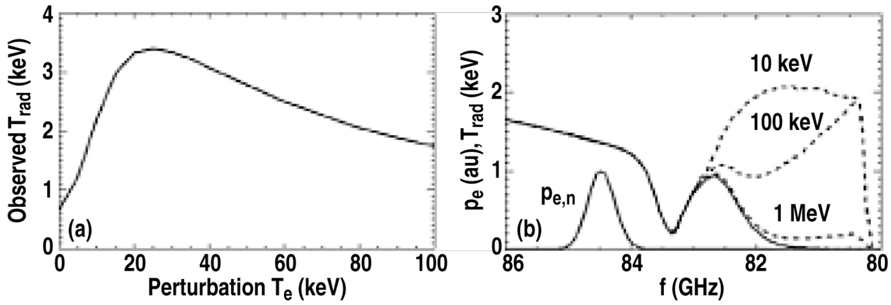

Fig. 2. (a) The variation in peak observed radiation temperature is shown as a function of local electron temperature for a modeled suprathermal perturbation centered at ρ = 0.95. (b) Equilibrium (solid line) and perturbed (dashed lines) profiles of radiation temperature are plotted for perturbations having peak electron temperatures of 10, 100, and 1000 keV. Also shown is the normalized pressure perturbation, $p_{e,n}$, centered at a cold plasma ECE resonance of 85 GHz. Perturbations in radiation temperature due to incoherent cyclotron oscillations decrease at runaway energies and are localized to a region between 80 and 83 GHz. This region of frequency space is bounded by the right-hand cutoff frequency at the location of the perturbation and the peak in weakly reabsorbed, optically thin emission described in Ref. [6] and appearing here at 83 GHz. Equilibrium plasma profiles are consistent with shot 148762.

Similar intense radiation spikes have been observed during QH-mode plasmas on DIII-D, when ELMs are suppressed by an edge harmonic oscillation (EHO) that produces a coherent fluctuation of the pedestal temperature and density [10]. Spikes observed during shot 146473 are more regular and often less intense than those observed during type-I ELMs. The duration of intense emission is equally brief, lasting only a few μs, but the origin of emission remains more localized near the LCFS in both real space and in frequency as mapped to cold plasma resonances. Furthermore, poloidal propagation in the laboratory frame is regular, and in the same direction and apparent poloidal velocity as the n = 1 EHO. An example is shown in Fig. 3, and is consistent with findings reported in Ref. [11], where spikes appearing on the fast ECE radiometer were shown to appear at well-defined phases of observed EHOs.

Based on the available evidence, a reasonable conjecture is that the intense emission described above is coherent radiation due to the collective behavior of electrons in the pedestal as they interact with periodic modulations of the magnetic field associated with MHD modes [12]. The underlying instability leading to an ELM crash is believed to be a fast growing peeling-ballooning mode with a periodic, field-aligned structure similar to that of the EHO [5,13]. Though this structure has yet to be directly diagnosed in 2D by ECE-I on DIII-D due to the intense emission spikes that obscure more subtle perturbations at these times, magnetic fluctuations on fast sampling Mirnov probes reveal that a perturbation in B_r and the onset of emission spikes are temporally correlated. Again, this onset time is ~100 μs before the rise in divertor D_α emission. This warrants further exploration, not only for the purpose of developing novel diagnostic capabilities, but also for its potential impact on ELM theory and the operation of ITER, where the prevalence and impact of this phenomenon has not been evaluated.

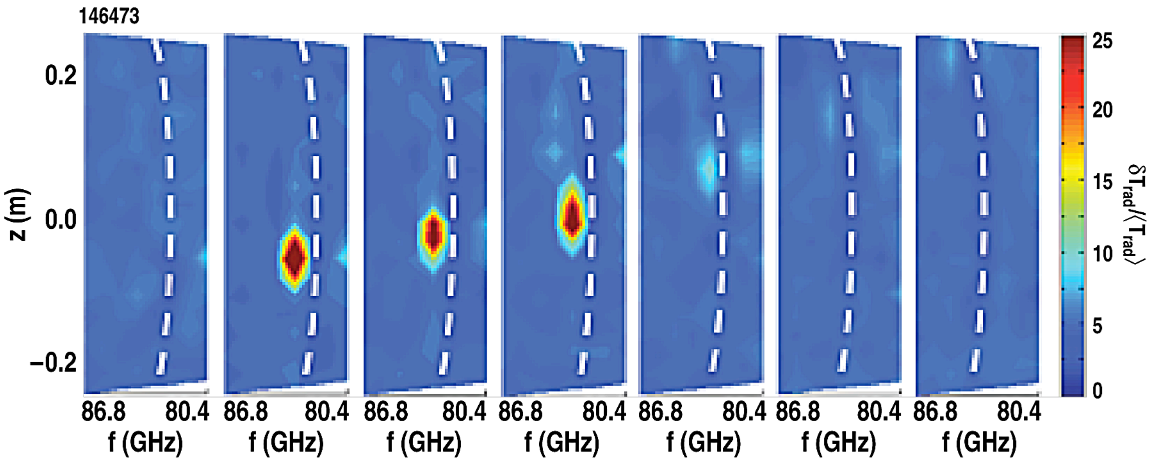

Fig. 3. A radiating structure imaged in shot 146473 propagates poloidally in phase with an $n = 1$ EHO. Intense radiation is observed in frames 2–4. Before and after these times, a faint perturbation is visible at frequencies above and below the cold resonance of the LCFS (white dashed line), consistent with the image predicted in Ref. [6] for incoherent radiation from a thermal perturbation localized near the LCFS in real space. Images span 6 μs at 1 μs intervals, beginning at $t = 2.807$ s.

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