A Brief History and Evolution of Electron Cyclotron Emission Imaging (ECEI) Systems

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Abstract*—This paper presents the history and evolution of Electron Cyclotron Emission Imaging (ECEI) systems, from its first applications in the mid 1990-ies until the present. ECEI has emerged as a transformative diagnostic tool for magnetically confined fusion plasmas, providing 2D measurements of electron temperature fluctuations with high resolution (centimeter-scale, and microsecond). Deployed globally on major fusion devices (e.g., ASDEX-Upgrade, DIII-D, KSTAR, EAST), ECEI has enabled critical studies of plasma instabilities, including sawtooth crashes, edge-localized modes (ELMs), and energetic particle driven instabilities. Recent breakthroughs with millimeter-wave system-on-chip technology applications have significantly enhanced ECEI performance, achieving 400× higher signal gain, 85% lower noise, and a 2000× footprint reduction. The 2024 development of radiation-hardened GaN-based receiver chips further ensures compatibility with reactor harsh environments. Additionally, AI-driven analysis has expanded ECEI's diagnostic capabilities, enabling early disruption prediction, plasma shape detection, and locked mode identification with greater accuracy than the conventional diagnostics. These advancements position millimeter-wave diagnostics as the key for next-generation fusion reactors, meeting demands for compact integration, neutron tolerance, and real-time stability control. Future developments will focus on further optimizing ECEI for Fusion Pilot Plant (FPP) applications, solidifying its role in enabling stable, high-performance plasmas.

I. INTRODUCTION

OVER the past three decades, advancements in millimeter-wave imaging technology have significantly enhanced high spatiotemporal resolution measurements in various fields, particularly in fusion plasma diagnostics. Multi-dimensional diagnostics have not only provided critical experimental data and new physical insights into magnetically confined plasmas, but have also enabled breakthroughs in AI-driven machine learning applications. These developments have improved predictive capabilities for plasma instabilities, offering essential preemptive feedback control and risk mitigation for future fusion reactors. This report reviews key milestones in the design, prototyping, and technological evolution of Electron Cyclotron Emission Imaging (ECEI), highlighting its transformative impact on diagnostic capabilities.

II. HISTORY AND EVOLUTION OF ECEI

As a passive diagnostic tool, ECEI measures millimeter-wave radiation emitted by magnetically confined plasmas, enabling the characterization of electron temperature profiles and plasma instabilities. It has been widely deployed on major fusion devices worldwide, including ASDEX-Upgrade and TEXTOR (Germany), RTP (Netherlands), DIII-D and TEXT (USA), LHD (Japan), WEST (France), KSTAR (South Korea), as well as HT-7, EAST, HL-2A, HL-3, and J-TEXT (China). Compared to conventional 1D ECE radiometers, ECEI employs receiver arrays and high-resolution millimeter-wave optics to achieve centimeter-scale, microsecond-resolution measurements of electron temperature fluctuations.

The non-invasive nature and low maintenance requirements of ECEI have made it a preferred diagnostic in fusion research. The first-generation ECEI system was developed in the mid-1990s for the TEXT (USA) and RTP (Netherlands) tokamaks [1]. Subsequent upgrades in back-end electronics enabled its implementation on TEXTOR [2,3], where it facilitated simultaneous measurements of electron temperature fluctuations (by ECEI) and electron density fluctuations (by Microwave Imaging Reflectometry, MIR). The visualization of magnetic islands [4] and studies of heat pulse propagation [5] further demonstrated ECEI's capability to resolve fine-scale plasma dynamics.

To better investigate magnetohydrodynamic (MHD) instabilities, high-gain antennas were later integrated into ECEI systems on major fusion devices such as ASDEX-Upgrade [6], DIII-D [7], KSTAR [8], EAST [9], HL-2A [10], J-TEXT [11], and LHD [12]. Coupled with advancements in electronics and millimeter-wave optics [13], these high-resolution ECEI systems have delivered unprecedented diagnostic performance, enabling studies of key plasma phenomena, including energetic particle instabilities [14], sawtooth crashes [15], edge-localized modes (ELMs) [16], and disruption prediction [17].

III. TOWARDS APPLICATION IN FUSION PILOT PLANTS

As magnetic confinement research progresses toward the Fusion Pilot Plant (FPP) era, diagnostic requirements have evolved, demanding higher integration, enhanced neutron radiation tolerance, reduced port openings, broader parameter coverage, and a more sensitive instability prediction. In response, millimeter-wave diagnostics have undergone targeted optimization. In 2019, a breakthrough ECEI system based on millimeter-wave system-on-chip (SoC) technology (Fig. 1) was successfully deployed on the DIII-D tokamak [18]. Compared to conventional systems, this innovation achieved a 400-fold increase in signal gain (improved signal-to-noise ratio), a reduction in electronic noise to 15% of previous levels (higher measurement precision), a footprint reduction by a factor of 2000 (meeting compact integration needs), and a maintenance-free operation record of 5.5 years (fulfilling reactor-grade reliability demands). This milestone has set a critical precedent for future FPP and fusion reactor diagnostics. Further advancing the field, the first wide-bandgap-based (Gallium Nitride) millimeter-wave receiver chip was developed in 2024 [19], demonstrating the feasibility of radiation-hardened (rad-hard) millimeter-wave diagnostics—essential for reactor environments.

In parallel with hardware advancements, innovations in data analysis have expanded ECEI's diagnostic scope. By leveraging the “optical grey" emission characteristics in the plasma boundary and scrape-off layer (SOL), ECEI has been applied to determine the position of the last closed flux surface (LCFS) [20] (Fig. 2). On DIII-D, ECEI-derived measurements showed excellent agreement with EFIT reconstructions (error <5 mm). Additionally, dual-ECE (combining ECE and ECEI) has enabled early-stage detection of locked modes (Fig. 3), providing warnings 200 ms earlier than Mirnov coils and 800 ms earlier than standard ECE. These analytical breakthroughs stem from the synergy between advanced millimeter-wave diagnostics and AI-driven techniques.

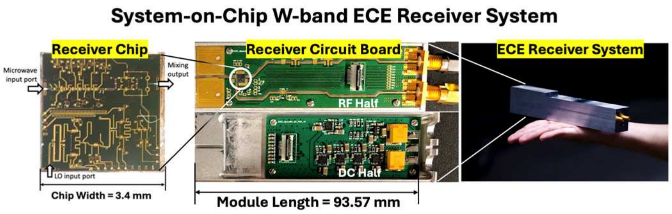

Figure 1. *Pioneering SoC ECE receiver system based on the GaAs W-band chip, enabling compact diagnostics on DIII-D since 2019.*

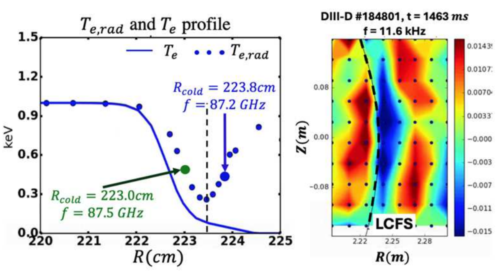

Figure 2. *(Left) Electron radiation temperature and electron temperature profiles at the low-field-side plasma boundary. The minimum radiation temperature position remains near the low field side last closed flux surface (LCFS). (Right) The LCFS measurement (obtained by ECEI) shows excellent agreement with DIII-D EFIT, with a discrepancy of less than 5 mm.*

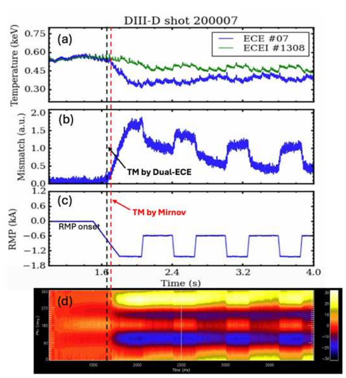

Figure 3. *Lock mode measurement based on dual-ECE method. (a) Signals of channel # 12 of ECE and calibrated channel # 1308 of ECEI of shot # 200007; (b) Mismatch between channel # 12 of ECE and channel # 1308 of ECEI; (c) RMP current; (d) Lock mode confirmed by Mirnov coil.*

IV. Summary

In three decades, ECE Imaging has grown from a technique to measure fluctuations in the electron temperature profile by scanning on a shot-to-shot basis to a versatile, compact, radiation hard, supersensitive diagnostic for 2D temperature measurements in a large plasma volume. The diagnostic has demonstrated its merits in automated plasma control and disruption prevention.

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