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Recent Results from Electron Cyclotron Emission (ECE) Radiometer diagnostics in the presence of Electron Cyclotron Resonance Heating (ECRH)

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Abstract. Besides furnishing localized spatial and temporal electron temperature measurements, Electron Cyclotron Emission (ECE) diagnostics are routinely employed across various tokamaks for diverse physics investigations, encompassing MHD localizations, transport studies, and fluctuation measurements. Variations in the bulk of the electron distribution function manifest as alterations in ECE signatures, often attributable to the presence of fast electrons induced by auxiliary heating mechanisms such as Electron Cyclotron Resonance Heating (ECRH). This manuscript delves into the scrutiny of such interactions on ECE spectra leveraging a newly devised 16-channel ECE radiometer diagnostic. The manuscript delineates the impact of ECRH application, including pre-ionization and heating, resulting in ECE signal saturation and an expected rise in electron temperature (T_e) respectively. Furthermore, the discourse explores instabilities potentially induced by high-energy electrons stemming from ECRH, focusing initial observations on runaway discharges characterized by relaxation oscillations in ECE, Soft X-ray (SXR), CIII, and H_α emissions. The backdrop of weakly ionized plasma with low electron density (n_e) and temperature (T_e), coupled with ECRH, fosters the generation of runaway electrons and corresponding relaxation oscillations in bulk plasma parameters. Additionally, a distinct surge in the ECE signature emerges upon cessation of the ECRH pulse, with no discernible variation in other bulk plasma parameters. Given that ECE signatures are susceptible to changes in both energy and pitch angle, this abrupt amplitude rise likely arises from Pitch Angle Scattering (PAS), potentially prompted by the sudden de-acceleration of fast electrons engendered by the ECRH pulse.

1 Introduction

Electrons within magnetically confined tokamak plasma emit Electron Cyclotron Emission (ECE) radiation as they spiral helically due to the influence of the Lorentz force [1]. Typically falling within the μ-wave to mm-wave range of the electromagnetic spectrum, this emission is probed and analyzed using sophisticated receiver systems. These systems encompass various optical and quasi-optical instruments such as Radiometers [3-5], Michelson Interferometers [6], and Grating polychromators [7]. ECE radiometry emerges as a potent diagnostic tool for capturing thermal electron temperature profiles and fluctuations with exceptional spatial and temporal resolutions in Maxwellian plasmas. By detecting alterations in electron dynamics stemming from deviations in the Maxwellian distribution, ECE offers valuable qualitative insights [8, 9].The interaction between non-thermal particles and Electron Cyclotron Emission (ECE) signatures in tokamak plasma is a subject of considerable interest and investigation. Non-thermal particles, such as fast electrons produced through mechanisms like Electron Cyclotron Resonance Heating (ECRH), have the potential to disrupt the electron distribution function within the plasma. These disruptions manifest as fluctuations in the ECE signatures, impacting the precision of temperature measurements and other diagnostic assessments. One significant consequence of non-thermal particles on ECE signatures is the modification of electron temperature measurements. The introduction of fast electrons into the plasma via ECRH or similar auxiliary heating techniques can lead to deviations in the overall electron distribution, resulting in the observed ECE spectra. This discrepancy may cause the electron temperature to be either overestimated or underestimated if not appropriately addressed in the analysis.

Apart from discrepancies, the presence of non-thermal particles can trigger instabilities in the plasma, adding further complexity to the interpretation of ECE data. High-energy electrons have the potential to initiate phenomena such as runaway electron generation or relaxation oscillations, which can alter the ECE signals and obscure the underlying dynamics of the plasma. Additionally, non-thermal particles can influence the pitch angle distribution of electrons within the

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plasma, leading to changes in the polarization of emitted radiation observed in ECE measurements. This modulation of polarization introduces additional challenges in interpreting ECE spectra and may require advanced modeling techniques to accurately extract plasma parameters.

To study plasma electron temperature evolution, Tokamak research often relies on Electron Cyclotron Emission (ECE) diagnostics [10–14]. Multi-channel wideband radiometers find extensive usage in various tokamaks and stellarators for thermal measurements, employing instrumentations in the GHz range. A 32-channel heterodyne radiometer covering the frequency range of 104 to 167 GHz for a toroidal magnetic field of 2.3T is designed for temperature measurements at EAST tokamak [15]. On one hand, where the ECE measurements provide localized thermal measurement for optically thick plasma, for optically thin cases, the non-thermal ECE radiation is broad-spectrum and non-localized. ECE radiometers can also be used for other physics studies like at ASDEX tokamak a 60-channel radiometer is used for real-time NTM control applications [16]. At J-TEXT the estimation of magnetic island width by the fluctuations of the electron cyclotron emission radiometer [17].

The focus of this manuscript lies in detailing the design and performance of ECE radiometer system, specifically examining its efficacy in capturing both thermal and non-thermal phenomena, particularly in the context of Electron Cyclotron Resonance Heating (ECRH). Section 2 delves into the experimental setup, outlining the arrangement used for data collection. In Section 3, the manuscript presents an in-depth analysis of the response of the ECE radiometer diagnostic, elucidating its ability to discern between thermal and non-thermal electron distributions induced by ECRH, both for pre-ionization and heating objectives. Additionally, it explores the emergence of instabilities resulting from the generation of high-energy electrons facilitated by the utilization of a high-power ECRH system. Finally, Section 4 provides a comprehensive conclusion, summarizing the key findings and implications drawn from the investigation.

2 Experimental arrangement

ADITYA-Upgrade (ADITYA-U) is a medium sized tokamak with a major radius of R=0.75 m and minor radius of a=0.25 m. A maximum toroidal magnetic field of up to B_T=1.5 T is generated using 20 numbers of toroidal magnetic field coils that are spaced symmetrically [18]. The ADITYA-U facility is engineered to generate a circular plasma featuring a plasma current ranging from approximately 150 to 250 kA, with a plasma duration lasting around 250 to 300 ms. The electron density, averaged across the chord, falls within the range of 3 to 5 × 10^{19} m^{-3}, while the electron temperature typically spans from 500 to 800 eV. Furthermore, ADITYA-U is configured to produce shaped plasmas characterized by a plasma current ranging from roughly 100 to 150 kA, an elongation (k) of approximately 1.1 to 1.2, and a triangularity of about 0.45.

Utilizing a 42GHz – 500kW Gyrotron as the Electron Cyclotron Resonance Heating (ECRH) system for plasma start-up and heating has significantly propelled advancements at ADITYA-U. This system has proven instrumental in overcoming previous limitations in low-loop voltage start-up and ECR heating. Former experiments were restricted to single EC pulses due to constraints in the power supply infrastructure [19]. However, recent enhancements to the 42 GHz Gyrotron's power supply, including the integration of an advanced anode power system, have revolutionized its capabilities. With an impressive rise and fall time of approximately 1ms, this upgraded system now facilitates multi-pulse operation. Such modifications offer a newfound flexibility in controlling pulse duration and ECRH power, tailoring operations to specific experimental needs [24]. Noteworthy is the recognition that breakdown initiation necessitates lower ECH power compared to the heating processes, where higher power levels prove more effective. Hence, the ability to adjust pulse duration and ECRH power levels as required, provides a crucial asset in optimizing experimental outcomes for both breakdown initiation and heating processes.

An operational 16-channel wideband super-heterodyne ECE radiometer system at ADITYA-U measures 2^{nd} harmonic EC emission. The frequency range (RF) covered is 64-83 GHz, enabling localized temperature measurements at 16 radial locations (*see Fig.1*) in a Maxwellian plasma. To meet experimental requirements for EC measurements across a range of toroidal magnetic fields (B_T) at ADITYA-U, a simple and cost-effective fixed Intermediate Frequency (IF) receiver of 1-20GHz is integrated with the RF. This design avoids complex sweep technologies and costly hardware constraints resulting from cyclotron frequency dependence on B_T [20].

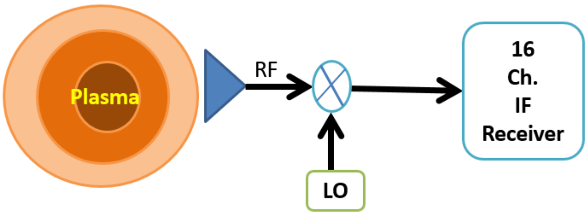

Fig. 1. Layout of the measurements from the ECE radiometer receiver from plasma.

The E-band antenna (*operating within the 60-90GHz range*) captures Electron Cyclotron (EC) emissions from the plasma and channels them through oversized waveguides to the receiver system. Upon reception, the radiation undergoes band pass filtering (BPF) to isolate the desired second harmonic range of 64-83GHz, with minimal pass-band loss

(<1.2dB). Subsequently, it undergoes initial down-conversion to an intermediate frequency (IF) spanning 1-20 GHz. This IF signal is then directed to a 16-channel fixed frequency receiver. Within the IF receiver, a secondary down-conversion takes place using individual local oscillators (LOs) and mixers, effectively reducing the first IF to a range between a few KHz and 1.18GHz, termed the second IF. This second IF is distributed across the 16 channels, with the first channel covering 1-2.18GHz and the 16th channel spanning 18.8-20GHz. Detectors with a sensitivity of 100mV/mW demodulate the signal, converting it into voltage for further processing.

3 Experimental observations and investigations

The presence of non-thermal particles introduces distortions in ECE spectra, providing valuable insights into their characteristics. These distortions arise from alterations in the electron velocity distribution, often induced by the presence of fast or high-energy electrons generated during disruptions or through the utilization of alternate and auxiliary heating mechanisms such as ECRH and LHCD. Compared to alternative techniques, ECRH offers notable advantages including efficient coupling, localized power deposition, easy launching, and precise directionality, making it a preferred method for studying non-thermal phenomena [21]. Information about these non-thermal particles can be obtained from ECE measurements.

At ADITYA-U, the ECRH system serves dual purposes: facilitating pre-ionization/breakdown with low loop voltage operation during single-pulse scenarios and providing heating through the use of second or multiple pulses to meet experimental requirements. Although the primary objective of the ECE radiometer diagnostic is to provide time-resolved spectroscopy of electron cyclotron emission, enabling the dynamic evolution of the electron temperature profile to be tracked over time [15], the initial observations regarding the presence of fast electrons generated by the application of ECRH at ADITYA-U will be discussed in the subsequent sections, shedding further light on the interaction between ECRH and non-thermal particles in tokamak plasmas

3.1 Observation from ECE during ECRH pre-ionisation / breakdown

As the applied electric field constantly accelerates, the initially Maxwellian electron distribution begins to develop a runaway tail. This acceleration process is further enhanced by the application of high power through Electron Cyclotron Resonance Heating (ECRH). During plasma start-up, when the density is typically low and the plasma is optically thin, the ECE signal is primarily influenced not by the bulk electron temperature but rather by the cyclotron radiation emitted by supra-thermal electrons, which is broad and non-local in nature. The effect of these supra-thermal electrons, termed non-thermals, is observed as a saturation of the ECE signals, particularly when ECRH is utilized for plasma breakdown at low loop voltages. At ADITYA-U, the standard start-up voltage is set at 20 V with hydrogen prefill. However, sustained breakdowns have been achieved with voltages as low as ∼10 to 13 V/m when approximately 300 kW of ECRH power is applied during the initial 60 ms, effectively accomplishing pre-ionization at the resonance location.

Figure 2 depicts the temporal evolution of various plasma discharge parameters for discharge #32584, including a plasma current of 126kA (Fig2a), a discharge duration of 253ms, and a toroidal magnetic field of B_T=1.28T. During this discharge, a single ECRH pulse (-40ms to 20ms, Fig2e) is employed for pre-ionization, aiming to reduce the high loop voltage consumption typically associated with plasma start-up and breakdown procedures. Notably, during pre-ionization, the discharge characteristics exhibit a non-Maxwellian distribution, with low density (Fig 2c) contributing to a higher generation of non-thermal or relativistic electrons, resulting in the observed saturation of the ECE signals, as illustrated in Fig. 2d.

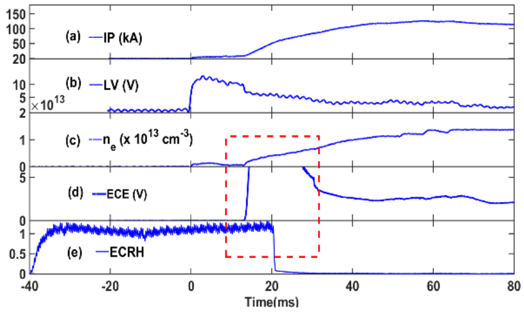

Fig.2 shows the temporal evolution of various plasma parameters (a) Plasma current (I_P) (b) Loop voltage (LV) (c) plasma density (n_e) (d) central channel ECE amplitude and, (e) ECRH pulse

3.2 Observation from ECE during ECRH heating

Similar to other heating methods, ECRH has witnessed a continuous refinement in its applications, progressing from bulk heating to profile tailoring and ultimately to distribution function engineering [28]. In contrast to alternative techniques, ECRH offers distinct advantages, including efficient coupling with the plasma, precise localization of power deposition, straightforward launching procedures, and precise control over directionality. Experimental assessments, incorporating measurements of hard X-ray (HXR) emission and Electron Cyclotron Emission (ECE) data, are employed to investigate the impact of ECRH on the electron distribution function. These analyses provide a comprehensive understanding of how ECRH influences electron behaviour within the plasma, thereby illuminating its efficacy in manipulating plasma properties for fusion research and related applications.

Figure 3 illustrates the temporal evolution of various discharge parameters for a normal ohmic discharge (#32563) at the ADITYA-U tokamak. This specific discharge showcases a maximum plasma current (I_P) of approximately 109kA, a peak density of n_e~1.4 x $10^{19}$$m^{-3}$ for a magnetic field strength (B_T) of 1.28T, and a central temperature exceeding 370eV as measured by the ECE diagnostic. As the ECRH heating pulse is applied from 52ms to 131ms, a notable increase is observed in the ECE signals accompanied by robust HXR emissions. This rise indicates an elevation in the radiative temperature as detected by the central channel of the ECE radiometer

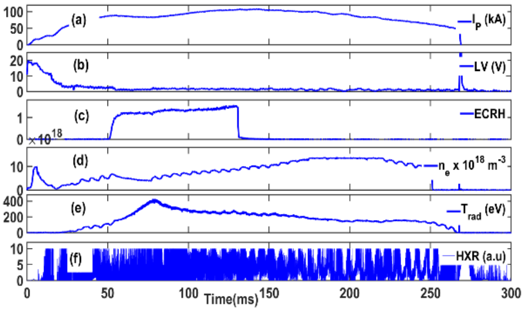

Fig.3. Temporal evolution of various plasma parameters (a) Plasma current (I_P) (b) Loop voltage (LV) (c) ECRH pulse (d) electron density (n_e) (e) radiation temperature measurements using ECE radiometer (T_{rad}) and (f) Hard X-ray (HXR) amplitude.

3.3 ECRH cause of instabilities

3.3.1 Runaway triggered discharges

Figure 4 depicts the plasma discharge characteristics for discharge #34241, showcasing a plasma current exceeding 100kA, a duration of 200ms, and a toroidal magnetic field strength of B_T=1.28T. Two distinct ECRH pulses are employed: the first for pre-ionization (-33ms to 26ms) and the second for heating (66.5ms to 111ms). ECRH plays a pivotal role in generating fast electrons, injecting energy into the Maxwellian tail of the electron distribution, thereby inducing relaxation oscillations like the Runaway-triggered spikes (RATS) instability [22]. Observations of the above discharge reveal a transformation from an ohmic discharge to a runaway discharge, characterized by weak ionization and extremely low background plasma temperatures and densities. These conditions are conducive to the generation of runaway electrons. The ensuing runaway discharges manifest relaxation instabilities across various plasma parameters, including density (n_e), loop voltage (LV), and H-alpha signals.

Remarkably, spikes in loop voltage consistently coincide with spikes in H_α emissions, establishing a direct correlation with the phenomenon of Runaway triggered spikes (RATS). Furthermore, the rise in density occurs concurrently, a phenomenon achievable only when a low-temperature background plasma is suddenly energized by the instability of runaway electron beams, supported by ECRH.

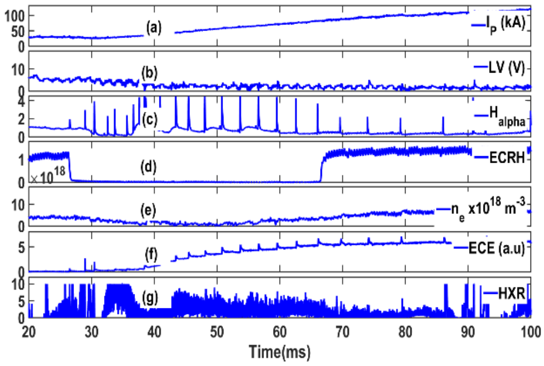

Fig.4. Temporal evolution of various plasma parameters (a) Plasma current (I_P) (b) Loop voltage (LV) (c) H_{alpha} (d) ECRH pulse (e) electron density (n_e) (f) ECE amplitude (g) hard X-ray (HXR)

3.3.2 Pitch angle scattering (PAS)

The electron cyclotron emission (ECE) diagnostic is widely employed to monitor both spatial and temporal alterations in electron temperature within Maxwellian plasma. However, its sensitivity to fluctuations in energy and pitch angle also enables effective characterization of runaway electrons [9]. These electrons emit broad-spectrum cyclotron radiation, contributing to the formation of non-thermal ECE spectra.

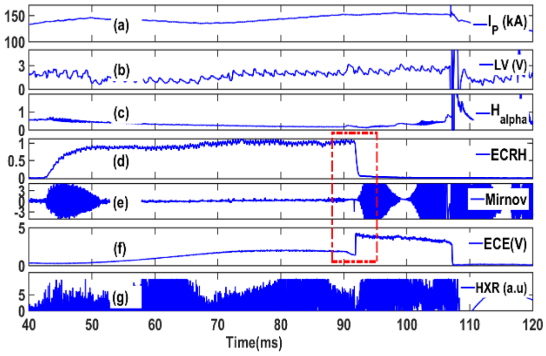

Fig.5. Temporal evolution of various plasma parameters
a) Plasma current (IP) b) Loop voltage c)H_α d) ECRH e) Mirnov osc. F) ECE amplitude and f) HXR amplitude.

Figure 6 illustrates the plasma discharge characteristics for discharge #33688, featuring a plasma current exceeding 65kA, for a toroidal magnetic field of B_T=1.28T. A single ECR pulse is applied for 42ms to 92 ms for the intention of plasma heating.

The application of the ECRH pulse leads to a noticeable rise in the ECE signature, not promptly seen in other bulk plasma parameters. However, upon the sudden cessation of the ECRH pulse, the presence of fast electrons, generated by ECRH get de-accelerated. This sudden de-acceleration of fast electrons could be the reason to trigger a sharp increase in the ECE signature, referred to as the Pitch Angle Scattering (PAS) event. PAS induces a rapid surge in the ECE signals, with an amplitude rise of approximately 10-20% occurring within a few microseconds. This interaction results in the redistribution of magnetic flux lines, altering the perpendicular velocity and/or energy parameters of the fast electrons.

4 Conclusion

At ADITYA-U, an advanced 16-channel wideband super-heterodyne Electron Cyclotron Emission (ECE) radiometer system is successfully operational. This system efficiently captures EC emission within a frequency range spanning from 64 to 83 GHz, enabling localized electron temperature measurements at 16 distinct radial locations within the plasma. Leveraging the sensitivity of ECE signals to both thermal and non-thermal electron distributions, the author has tried to qualitatively explore the diverse electron dynamics occurring during the pulsed operation of Electron Cyclotron Resonance Heating (ECRH), employed for both heating and pre-ionization purposes. In addition to electron & radiation temperature measurements, the ECE radiometer signatures are examined to provide an primary investigation into various instabilities arising from the presence of fast electrons generated by ECRH application. Notable instabilities include the Runaway-triggered spikes (RATS) and Pitch Angle Scattering (PAS). This comprehensive analysis aims to deepen our understanding of plasma behaviour under ECRH-induced conditions, paving the way for enhanced control and optimization of fusion processes

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