Contribution ID: **1240** Type: **Regular Poster**

Resolving the dispersion of plasma waves by measuring the modulation of electron cyclotron emissions

Tuesday 11 May 2021 18:25 (20 minutes)

Plasma waves naturally occur in various forms in magnetically confined plasmas. With a broad categorization into cold waves, hot (kinetic) waves, and coupled cold-hot waves, the plasma waves play integral functions in fusion plasma physics, such as particle confinement, fluid instabilities, and radiative processes. Some plasma waves, in particular low-frequency electrostatic (ES) waves, affect the diffusive transport of particles 1. Alfven waves and ion cyclotron harmonic waves interact with energetic particles, altering the energy distribution of the particles [2, 3]. The emission of electron cyclotron waves is an important channel of radiative loss of energy.

The amplitude and dispersion relation of each plasma wave depend on the local plasma parameters of the region where the wave is excited. The best example is the electron cyclotron emission (ECE); its frequency is proportional to the local magnetic field strength, and the intensity is proportional to the local electron temperature. The ECE radiometry is one of the most reliable diagnostics for the measurement of the electron temperature profile. On the KSTAR tokamak, an advanced imaging radiometry system has extended the capability of the conventional 1-D profile radiometry to 2D and quasi-3D imaging of magnetohydrodynamic (MHD) fluid modes and turbulent eddies [4].

Ion cyclotron emission (ICE) is another example that carries information about the plasma. On the KSTAR, we have developed a versatile radio frequency (RF) spectrometer system consisting of broadband antennas (about 0.1~2 GHz), 8-channel filter-banks, and high-speed digitizers [5]. Using the RF spectrometer, we recently showed that harmonic ICEs occur in the edge of an H-mode plasma [5], and the ICE spectrum depends on the distribution of energetic ions and the local electron density [6]. By fully integrating the RF spectrometer with the ECE imaging system, we found that the spectral change of ICEs has a high correlation with the state of the macroscopic fluid modes in the edge region [7], implying a mutual interaction between ICEs and fluid modes.

The ECE and ICE examples suggest that other plasma waves also have high potential as diagnostic signals. The existing RF diagnostics implemented in several tokamaks and linear machines use various forms of antennas, depending on the wave frequencies of interest. The use of antennas is a relatively easy and low-cost method of resolving the frequency spectrum of the RF emissions. However, the frequency spectrum measured by an antenna provides no information on the wavenumber, which makes it difficult (although not impossible) to determine the type of wave. Furthermore, the ES waves or the waves that attenuate too much before escaping the plasma boundary are beyond the reach of antennas.

We propose a new RF diagnostic system to enable local measurement of plasma waves and determination of wavenumber as well as frequency spectrum. The new concept relies on the idea that a plasma wave in the RF range can modulate the intensity of ECE. The modulation of ECE can be detected outside the vacuum vessel using the conventional mm-wave heterodyne technique. We have implemented the first such RF diagnostic system utilizing multiple mm-wave mixer antennas in the ECE imaging system on the KSTAR. The mm-wave-based RF (mwRF) diagnostic system provides high-resolution (~1 MHz) measurement with a broad frequency range (0.1~8 GHz).

We have applied the mwRF diagnostic to the plasma waves associated with a variety of MHD and kinetic phenomena such as sawtooth crashes, runaway electrons, and plasma disruptions. For the case of the edge transport barrier (pedestal) collapse, we observe intense narrow-band emissions in the whistler frequency range (~ 1 GHz). The measurements at two different toroidal positions (about 18.5° apart) show that intense waves of similar spectral characters are observed only along a specific direction (approximately the magnetic field line). This observation supports that the onset of pedestal collapse occurs at a localized region in the edge [8, 9] and generates RF waves propagating mostly parallel to the magnetic field line.

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We now use the mwRF diagnostic system to determine the wavenumber of the plasma waves embedded in the modulation of ECE emissions. We envision that passive diagnostics utilizing plasma waves will be one of the most practical solutions as reactor-relevant diagnostics beyond ITER. This work was supported by the NRF of Korea under grant No. NRF-2019M1A7A1A03088456 and BK21+ program.

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Session Classification: P2 Posters 2

Track Classification: Magnetic Fusion Experiments