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Advanced diagnostics for fusion plasma instabilities on the KSTAR tokamak

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1. Introduction

The Korea Superconducting Tokamak Advanced Research (KSTAR) program has been an innovative platform for the study of magnetically confined fusion plasmas. The high-precision engineering of the KSTAR tokamak achieved a nearly ideal axisymmetric magnetic field configuration with both the error fields and toroidal ripple fields being at least an order of magnitude better than those of all the existing tokamaks [1]. The superconducting coils provided long pulse operation, which achieved steady-state plasmas and enabled the study of magnetic hydrodynamic (MHD) instabilities and turbulence phenomena in such steady-state in contrast to the study of similar phenomena in non-steady states in the conventional tokamaks. The capability of steady-state operation also made the KSTAR an ideal experimental platform for perturbation studies such as plasma response to external resonant magnetic perturbation [2].

A suite of advanced imaging diagnostics have been developed to maximize the capabilities of the KSTAR tokamak for the study of MHD and turbulence physics on top of the above engineering merits. The advanced diagnostics include the electron cyclotron emission (ECE) imaging systems [3], the microwave imaging reflectometry [4], and the fast RF spectroscopic system [5]. These diagnostics have provided high resolution data on MHD, turbulence, and wave phenomena, respectively, with unprecedented details. Assisted by conventional profile diagnostics and probe systems on the KSTAR, the high resolution data enabled discoveries of many new phenomena such as quasi-stable flux tubes in the core [6], non-normal filamentary modes in the edge [7,8], the interaction between turbulence and MHD modes [9], quasi-coherent modes [10], and ion cyclotron harmonic waves [5].

In the following sections, brief summaries of the advanced diagnostic systems are provided with highlight physics results.

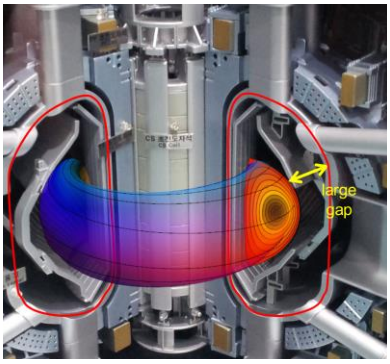

Figure 1 Cutaway view of the KSTAR tokamak. Ripples are about 5 x 10^{-4} of the toroidal field. Error fields are less than 10^{-5}

2. Electron Cyclotron Emission Imaging (ECEI)

The ECEI diagnostics on the KSTAR is based on the same mm-wave technologies used in the conventional ECE radiometry for the electron temperature (T_e) profile measurement. Each ECEI system [3] consists of a large-aperture mm-wave lens system, broadband mm-wave filters, an array of 24 vertically-aligned mm-wave heterodyne detectors, broadband local oscillators (covering the W-band), low-loss signal transmission line system, a set of 24 intermediate frequency (IF) modules, and digitizers. Each IF module separates the incoming signal from a single mm-wave mixer detector in the array into 8 frequency bands which corresponds to 8 different radial positions in the tokamak plasma. Thus, a single ECEI system provides 24 x 8 = 192 channels on a cross-sectional of the tokamak plasma with typical spatial resolution ~ 2–3 cm. The KSTAR has three ECEI systems, which has enabled quasi-3D imaging of MHD instabilities for the first time. Figure 2 shows a schematic view of the ECEI system on the KSTAR.

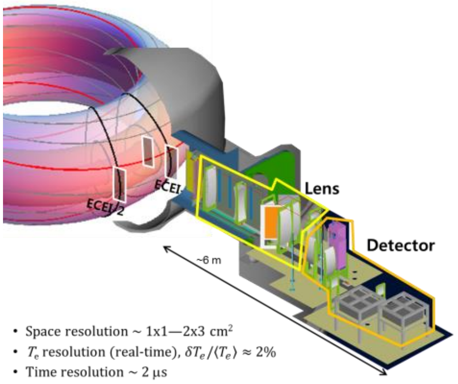

Figure 2 ECEI systems on the KSTAR.

Figure 3 is an example of quasi-3D images of core flux tubes [6], which are commonly observed in the KSTAR with localized heating. The example demonstrates the importance of quasi-stable flux tubes for the stability of tokamak plasma and at the same time reveals the limitations of the conventional MHD spectral theory based on the linear stability analysis.

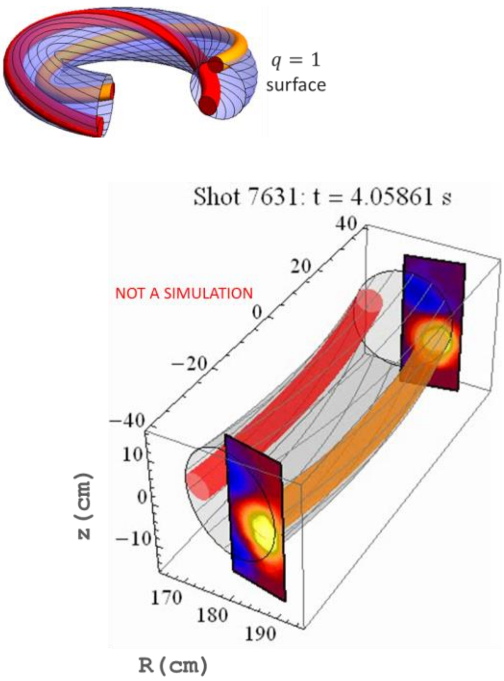

Figure 3 Dual flux tubes produced in the core region.

3. Microwave Imaging Reflectometry (MIR)

The MIR system [4] forms two Gaussian-like probe beams at several different frequencies through a large-aperture mm-wave imaging optics (See figure 4). The individual beams are reflected at the corresponding cutoff layer inside the plasma and the reflected beams are projected onto an array of 16 vertically-aligned mm-wave mixer detectors (similar to those in the ECEI system). The signal from each mixer is analyzed by IQ demodulator circuitry in the same way as in conventional reflectometry.

The MIR system provides high-resolution measurements of turbulence modes up to wavenumber of 3 cm^{-1} with the nominal time resolution of 2 μs. The MIR system revealed the existence of quasi-coherent modes [10] in the KSTAR L-mode and Ohmic discharges, which serves as an indirect evidence for turbulence driven by ion temperature gradient (ITG) [10].

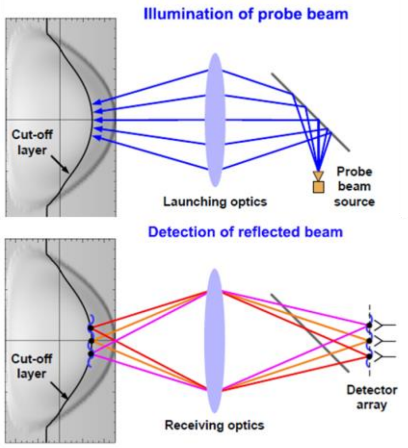

Figure 4 Working principle of the MIR system.

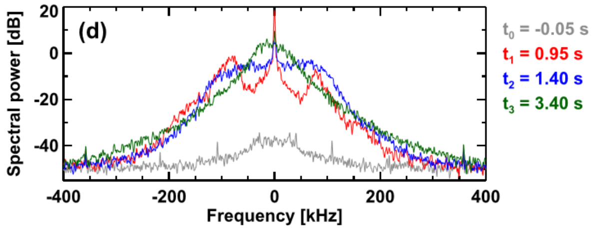

Figure 5 Turbulence spectrum measured by MIR (KSTAR shot18332). The red curve shows the QCM during the low density Ohmic phase.

4. RF spectrometer system

The RF spectrometer system was initially developed as an appendix to the ECEI system on the KSTAR in order to assist the detection of fast MHD events such as crash of edge-localized modes (ELM) and plasma disruption. A particular interest was put into the detection of high frequency waves above ion cyclotron (IC) frequency in the expectation that such fast events would involve magnetic reconnection and thereby generate whistler waves and IC harmonic waves. The RF spectrometer, schematically shown in figure 6, now consists of a set of broadband antennas covering the IC harmonic range (0.1—1 GHz), a set of mm-wave mixer antenna, filter bank modules, and high-speed digitizers. The branch of the mm-wave antenna resolves the waves in the 1—6 GHz by detecting modulations in the mm-wave ECE signals. High-spectral and high-time resolution measurements are achieved thanks to the modern high-speed digitization technology.

The simultaneous acquisition of the RF emission signals with ECE images [5] revealed that IC harmonic waves evolve in multiple stages through the edge transport barrier formation and subsequent ELM crash. The existence of IC harmonics were attributed to the energetic particle driven waves called magneto-acoustic cyclotron instabilities [11, 12]. The GHz band acquisition capability also confirmed the existence of whistler branch waves synchronized with the burst of ELM filament [5, 8]. The RF spectrometer is also being used to study the waves generated by runaway electrons.

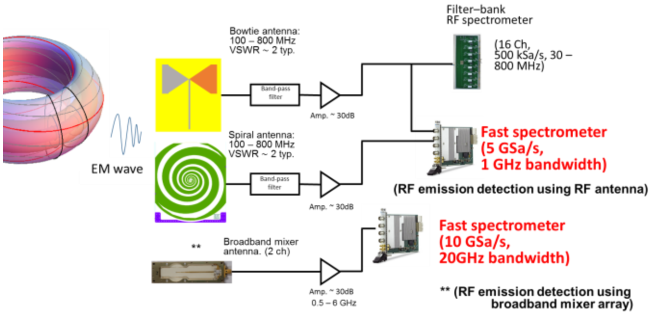

Figure 6 Schematic layout of the fast RF spectrometer system

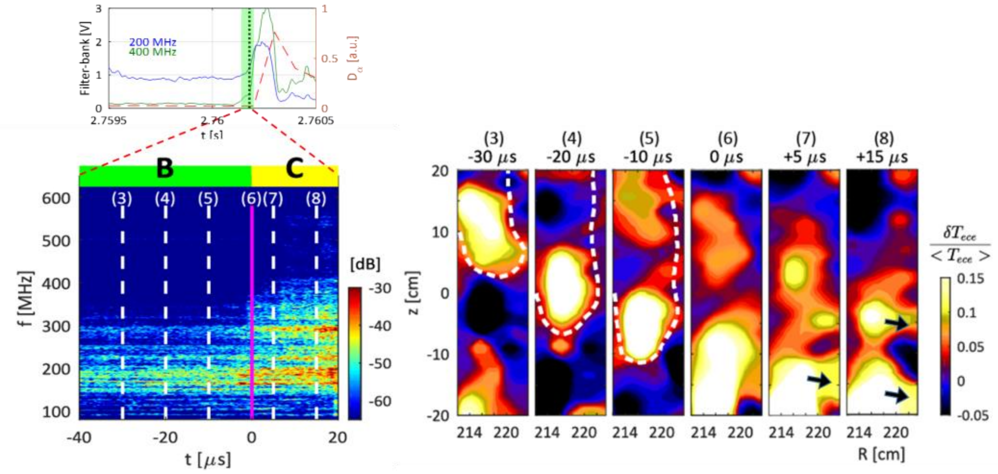

Figure 7 RF emission near the onset of ELM crash

5. Summary and prospects

The suite of advanced diagnostics have been developed on the KSTAR to provide high resolution data for MHD, turbulence, and waves. In the last decade, the KSTAR advanced diagnostics revolutionized the study of magnetized high-temperature plasmas by revealing previously unresolvable phenomena, revealed the prevalence of non-normal MHD modes challenging conventional wisdoms, and pioneered high-resolution wave measurements. The advanced diagnostics will continue to improve and contribute to the studies of fundamental plasma physics on the KSTAR.

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