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Evolution of Fusion Plasma Science and Advanced Diagnostics for Study of the Gap between Theory and Experiment

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Through active research of the fusion plasma science in large tokamaks (TFTR, JET, and JT-60U), confidence on experimental/theoretical progress led to developing the ITER project. The confidence may have come from a stable operation of the improved confinement regimes such as the H-mode and ITB mode, etc. However, it is notable that there is neither a transport theory that can confidently predict the confinement time nor a modelling for a preemptive control of the harmful MHD instabilities.

Theory of MHD instabilities is well understood, since it is based on Ohm's law and Maxwell's equations in a semi-symmetric geometry (e.g. cylindrical system with elongation, triangularity and toroidity). The geometric structure of MHD modes in a linear (saturated linear) phase can be accurately modeled with the basic MHD code as you can find in text books. Validation of the physics related to the linear (saturated linear) stage of the MHD mode can be confidently achieved with the measurement from the conventional 1-D or chordal 2-D data.

However, modeling of the MHD instabilities from the rapidly growing phase to the burst has been used for interpretation but could not be used for prediction. In order to challenge the complex physics problems in late stages of the MHD instabilities and turbulence, the first microwave imaging systems [electron cyclotron imaging (ECEi) and microwave imaging reflectometry (MIR) system] with high spatial and temporal resolution was developed to visualize the MHD instabilities and turbulence on TEXTOR device [1]. Nowadays, the ECEi system is a standard advanced diagnostics in majority of tokamaks including the KSTAR system with 3-D capability. The ECEi images have been utilized to explore the missing physics and/or to study the gap between observations and theoretical models. Examples of newly uncovered physics of the sawtooth, neo-classical tearing mode (NTM) and edge localized mode (ELM) instabilities are given in this paper [2].

The sawtooth instability is the most studied instability which is a repetitive fast crash of the current carrying *m/n=1/1* kink mode in the core of the plasma. The first physical model was the full reconnection model [3] and this model was rejected due to the predominantly faster crash time in observations and early measurements of core current density change (q_0) contradicting to the 1/1 kink mode instability condition ($q_0>1.0$ after the crash) used in this model. Numerous new theoretical models were developed and measurements of q_0 were performed for the last 40 years. It was found that the crash process of the dominant fast crash case is different from that of the slow crash case through the 2-D ECEi measurement. Here, the axisymmetry of the 1/1 kink mode prior to the crash time is the key for the two different crash time scales. Combination of the measured $q_0\sim1.0$ and a supplemental tearing mode experiment that is sensitive to the background q_0 proved that the q_0 went back to $q_0>1.0$ after the crash. The full reconnection model is correct after all.

The classical NTM instability is relatively well understood and accurate experimental determination of the stability parameter (Δ') and island size (ω_c) is important. Advantage of the 2-D ECEi data over 1-D data for this application is albeit and will be reviewed. The 2-D ECEi data is ideal for study of the disruption process and application plan of the real time control of the disruption induced by the NTM will be introduced. The coupling physics between the altered micro-turbulence due to presence of the 2/1 island and meso-scale MHD mode an important subject to be studied. Since the current modeling is based on independent estimation of the potential distribution in presence of the island, it is important to introduce the first principle based modeling for self-consistent study.

Enhanced understanding of the ELM instability is critical for preemptive control this instability in the H-mode plasma. The study of this instability has been dominated by D_α lights and visible camera images. Information of the ELM mode numbers and accurate bootstrap current is critical to improve the peeling-ballooning mode model for predictive capability. The KSTAR plasma is ideal for study the ELM instability and suppression mechanisms this instability with the resonant magnetic perturbation (RMP), since the KSTAR is equipped with the plasma almost free of error field, advanced IVCC for the control and 2/3-D ECEi system. The measured ELM mode was validated with the MHD code. Many new physics such as the time evolution of the ELM-crash in MHD time scale, in and out asymmetry, and coupling between the micro-turbulence induced by RMP and meso-scale ELM mode was achieved with the ECEi data. This work is supported by NSF #[redacted]

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