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Non-equilibrium and extreme state -Development and application of numerical diagnostic tools for plasma turbulence-
非平衡極限 ―乱流数値診断ツールの開発とその適用―

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Turbulence Diagnostic Simulator is an assembly of simulation codes for numerical diagnostics in magnetically confined plasmas. Several kinds of experimental diagnostics can be simulated by selecting combination of turbulence codes and numerical measurement modules. We have developed simulation modules for reflectometery and phase contrast imaging. By using these modules, numerical diagnostics of simulation data of 3-D turbulence are carried out to understand the structural formation mechanisms in the non-equilibrium and extreme state.

1. Introduction

It is necessary to deepen our knowledge of plasma turbulence for improving the confinement in fusion plasmas. Nonlinear coupling in multi-scale turbulence is one of the keys in the transport mechanism, and dynamical changes of the mean and fluctuation profiles must be measured with high spatio-temporal resolutions for identifying the mechanism. In this research, development of diagnostic tools is promoted by simulating detailed fluctuation measurements in experiments. Turbulence Diagnostic Simulator (TDS) [1], which is an assembly of simulation codes for numerical diagnostics in magnetically confined plasmas, is used as the platform for the development to accelerate the collaboration between the simulation and experiment. Development of a reflectometer using microwave frequency comb [2] and phase contrast imaging (PCI) [3] is explained in this presentation.

2. Turbulent Diagnostic Simulator

For turbulence analyses, we have been developing the assembly of codes, TDS. The TDS consists of two main parts; turbulence codes and modules simulating experimental diagnostics. Turbulent fields are produced by fluid simulations using a supercomputer. Calculations in several kinds of magnetic configurations, such as helical, tokamak and linear devices, are carried out, and time series data of three-dimensional (3-D) fluctuation fields are obtained. The data are transferred to a data storage. A large number of temporal points, which are sufficient for statistical analyses, are stored, so the data size is the order of tera-bytes in the case of toroidal plasmas. The stored data are analyzed using modules to simulate experimental diagnostics of turbulence, such as reflectometry, PCI, heavy ion beam probe and an electrostatic probe, and produce results that can be compared with experiments. The TDS includes the several turbulence codes and the several numerical measurement modules. The combination is selected in accordance with the research object.

3. Simulation of the reflectometry

The system of a microwave frequency comb reflectometer has been developed. An experimental test has been begun on the PANTA device in Kyushu University, which will be applied to the LHD experiment [2]. The principal of the diagnostic is as follows. The comb signal with the frequency range of 12 - 27 GHz and the frequency interval of 0.5 GHz is injected and reflected in the plasma. Each Fourier component of the microwave has time delay in accordance with its reflected point, so the density profile can be reconstructed from the detected comb signal. The phase of the carrier wave is precisely controlled with respect to the shape of the envelope. This experimental method is promising for the physics of plasma turbulence and transport.

For the reconstruction of the profiles, it is necessary to carry out a numerical simulation, so the routine to simulate the microwave frequency comb reflectometer has been developed in the TDS. The module of the ray tracing and full wave analysis of the RF wave in the integrated simulation code TASK [4] is introduced for the wave analysis. The original routine is modified to adjust to the cylindrical magnetic field configuration and the incident comb signal for the linear device. For the first step, calculation of the ray and the phase delay gives the evaluated output signal in accordance with the plasma density profile. Figure 1 shows an example of the incident and detected waveforms. Different Fourier components have the different reflected points as in Fig. 1 (c), which gives the detected signal as Fig. 1 (b). This simulation gives the insight to experimental observations, and will be extended to analyze both simulation and experimental data in the same routine.

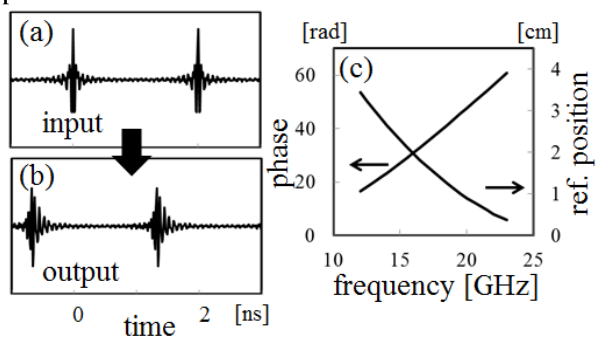

Fig.1: Simulation result of the (a) incident and (b) detected waveforms of the microwave frequency comb reflectometer. The phase delay in (c) gives the detected signal as (b). The incident comb signal has the frequency range of 12 - 27 GHz and the frequency interval of 0.5 GHz in this case.

4. Simulation of the Phase Contrast Imaging

The PCI is used for the measurement of density fluctuation with high temporal and wave number resolutions [3]. An injected laser beam is scattered by the density fluctuation, and interference between the scattered and unscattered reference beams gives the 2-D pattern of the fluctuation in the *k* space. The signals are given as the integral of the density fluctuation along the line of sight, so there is a problem to resolve the local values from the signals. The pitch angle of the magnetic field is used to help the identification in the LHD experiments [3]. Here we obtain the 2-D spectrum of the density fluctuation using test 3-D field data and simulation data, and compare those from local fluctuation and their integration along the beam path.

The direction of the detection beam can be selected arbitrarily in the simulation, and vertical one is used here. As for comparison, a test field perturbation localized around one radial position is used to calculate the 2-D wave number spectra of density fluctuation. Wave number k_x (wave number in the R direction) is given by combination of k_r and k_θ. The target fluctuation has its maximum amplitude near the midplane, so the correlation with the fluctuation at $z = 0$ describes the k_x spectrum form. On the other hand, the projection of k_r on the x direction becomes smaller at larger z, so the peaks of the correlation exist at the smaller k_x with fluctuations at larger z. The spectra are not symmetric in the z direction because k_x is the combination of k_r and k_θ. These dependences can be applied for identification of the local information. In the case of the nonlinear simulation data, low k_x modes with finite mode widths exist, and their overlapping with the broad band spectrum makes it difficult to identify the local fluctuations. In this way, simulation data can be used as a test field for interpretation of the measured signals.

5. Summary

TDS, which is an assembly of simulation codes for numerical diagnostics, has been developed to simulate several experimental diagnostics, such as reflectometory and phase contrast imaging. By using these diagnostic modules, numerical diagnostics of simulation data of 3-D turbulence are carried out to make comparison with experimental results for understand the structural formation mechanisms in the non-equilibrium and extreme state.

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