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—

N. Kasuya1,2, K. Kawadu3, H. Sento3, S. Inagaki1,2, A. Fukuyama2,4, K. Itoh2,5, S.-I. Itoh1,2
糟谷直宏1,2、河津賢太朗3、仙頭寛輝3、稲垣滋1,2、福山淳2,4、伊藤公孝2,5、伊藤早苗1,2

1Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan
2Research Center for Plasma Turbulence, Kyushu University, 6-1 Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan
3Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, 6-1 Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan
4Graduate School of Engineering, Kyoto University, Kyoto Daigaku Katsura, Saikyo-ku, Kyoto, Kyoto 615-8540, Japan
5National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan

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 reflectometory 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.](image)

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 $k_\theta$. 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 $k_\theta$. 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 reflectometry 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.

Acknowledgments

This work is supported by the Grant-in-Aid for Young Scientists (24760703), for Scientific Research (23244113, 21224014), by the collaboration program of NIFS (NIFS13KNST050, NIFS13KOC001) and of RIAM of Kyushu University.

References