Diffusive Transport Analysis in Low Aspect Ratio Reversed Field Pinch

Yasuo Nagamine[1], Atsushi Fukuyama[2], Shoichi Shiina[3] and Masamitsu Aizawa[1]

[1]*Institute of Quantum Science, Nihon University*
1-8-14 Kanda-Surugadai,Chiyoda-ku,Tokyo 101-8308, Japan
[2]*Department of Nuclear Engineering, Kyoto University*
Yoshida-Honcho, Sakyo-ku, Kyoto 606-8501, Japan
[3]*National Institute of Advanced Industrial Science and Technology*
Umezono, Tsukuba, Ibaraki 305-8568, Japan

1. Introduction

To evaluate confinement properties of the low aspect ratio reversed field pinch (RFP) plasma, diffusive transport analysis including the neoclassical and turbulent transport models is studied. As for the conventional RFP plasma with laeger aspect ratio, resistive magnetohydrodynamic transport analyses by using the theoretical model or three-dimensional numerical simulations based on the cylindrical approximation have been performed and shown to be nearly consistent with experimental results such as the confinement scaling in the standard ohmically driven RFP [1,2]. In the present RFP, it is considered that resistive diffusion in the relaxation process causes the anomalous transport of energy and particles. However, of transport phenomena in the steady state RFP without dynamo effect, the energy confinement time τ_E might be determined by anomalous transport due to micro-instabilities like in tokamaks. Mechanism of the turbulent transport due to micro-instabilities such as ITG modes is not understood well in the RFP.

In Ref.[3], linear gyro-kinetic calculations were applied to the RFP configuration to investigate the occurrence of ITG instabilities. This analysis reports ITG modes are in general stable in RFP plasmas in the area of experimental parameters.

In this study, we focus on the low aspect ratio configuration with shaped magnetic surface and neoclassical effects. We assume two-dimensional RFP configuration to understand a basic characteristic about this type of transport. It is expected to use the gyro-fluid model as the turbulent transport model, which describes the dynamics of a limited set of fluid moments of the gyro-kinetic equations. In diffusive transport analysis, we apply TASK code [4] to the RFP configuration. As preliminary calculations of the modified TASK code, equilibrium and transport analyses of the low aspect ratio RFP were performed using the neoclassical and basic turbulent transport models. It is necessary to apply advanced transport models stated above for more detailed analysis.

2. Low aspect ratio RFP

In this section we consider some characteristic features of the low aspect ratio RFP configuration. As for the equilibrium profile, the safety factor (q) value increases on the axis and decreases at the edge, while its profile flattens in the core region and sharpens in the edge as A decreases. So that the number of resonant surfaces decreases and also the toroidal mode number n decreases, that is, resonant tearing mode locations separate more from each other [6]. For example, at A=2.1 we can set the lowest mode m/n=1/4 at r=0.43 (m=1 is dominant in RFP). The elongation has the equivalent effect with the decrease of A. From the above, lowering A could lead to easily attaining Quasi-Single-Helicity (QSH) states [7] with high beta. A helical structure has also been observed experimentally in A=2 RFP device [8].

Another feature is expected to be the advantage of higher bootstrap current. A consideration of neoclassical effect in the RFP equilibrium has led to a significant fraction of bootstrap current in a low aspect ratio, which is quite important to a steady state operation as well as to a high beta stability [9]. The equilibrium attained is characterized by the hollow current profile of plasma self-induced current, which leads to the compatibility of the strong negative magnetic shear and the strong plasma paramagnetism due to the high pitch magnetic line of force toward the plasma boundary region, in addition to the relaxed-equilibrium state with a minimum energy at finite beta [10]. Due to both the large negative magnetic shear and the strong paramagnetism, the transport improvement is also expected in this configuration, which must be investigated by the transport simulation described in present paper.

3. TASK code

TASK (Transport Analysing System for TokamaK) code is an open source code which has been developed at Kyoto University [4,11]. This code consists of some modules calculating each physical process such as equilibrium, transport, wave propagation, etc. and analyzes the transport process of the whole nuclear burning plasma by integrating them.

In this study, we use equilibrium (EQ) and transport (TR) modules mainly for the diffusive transport analysis. In the TR module, some diffusive transport models based on the neoclassical transport theory and turbulent transport theory are implemented. Applied for the first time to the RFP configuration, the code is exploited for steady state calculations with the neoclassical and basic turbulent transport models. In order to include the description of the RFP geometry, some parts of the code need to be improved. The most fundamental improvement is related to the existence of 0 points of the toroidal magnetic field at the reversal surface [5].

4. Transport simulations

4-1. ST plasmas

Before applying to the RFP configuration, we performed the verification analysis of the modified TR transport module for the spherical tokamak (ST) plasma with a high β value like RFP. In tokamaks, so many transport analyses have been performed, and developed some turbulent transport models, such as gyro-kinetic or gyro-fluid simulations of ITG (Ion Temperature Gradient) instability and turbulence. Comparisons and physics basis of tokamak transport models and turbulence simulations are summarized in Ref. [12]. As major turbulent transport models, CDBM (Current Diffusive Ballooning Mode), GLF23, IFS/PPPL and Weiland models are employed in TASK code. In these models, it is considered that the CDBM model has difficulty in application to the RFP configuration. Three of the remainder are all models based on the gyro-fluid description.

The GLF23 model is a comprehensive drift-wave based model which describe the turbulent transport due to ion temperature gradient (ITG), trapped electron mode (TEM), and electron temperature gradient (ETG) micro-instabilities. It was formulated by approximating the linear growth rates of the three-dimensional (3-D) ballooning mode gyrokinetic stability code and the transport coefficients of 3-D nonlinear gyro-Landau-fluid simulations [13]. In tokamaks, such drift-wave based models have demonstrated good agreement with experimental data from a wide variety of discharges and have predicted the correct trends observed in dimensional similar expreriments [14].

In this study, we performed the transport analysis of the ST plasma using the GLF23 model and widely used Gyro-Bohm model. This analysis was carried out focusing on the evaluation of transport coefficients and temperature profiles calculated by these models as verification analysis. Therefore the effects such as ITB formation were not considered here. Also no further heating such as NBI is considered, so it is assumed that the plasma heating depends only on the Ohmic heating. By using the same equilibrium configuration, simulation results of two transport models mentioned above were compared. An aspect ratio A=2.0, ellipticity κ=1.4, triangularity δ=0.4, plasma current I_ϕ =0.3MA and central electron density $n_{e0}=1.0\times10^{-20}m^{-3}$ are assumed as equilibrium parameters of the ST plasma. Figure 1 shows the result of equilibrium and transport calculations: (a) equilibrium q-profile, (b), (c) temperature profiles predicted by the transport calculation of each model ((b):Gyro-Bohm model, (c):GLF23 model), where the density profile is held fixed in this calculation. As to the electron and ion transport coefficients, they became the peaked profile in the edge region in both models. It is considered that temperatures predicted by the Gyro-Bohm model became smaller since it has larger transport coefficients. In this analysis, it was shown that anomalous transport analysis by using TASK code was enabled in the ST plasma which was not described by the tokamak approximation.

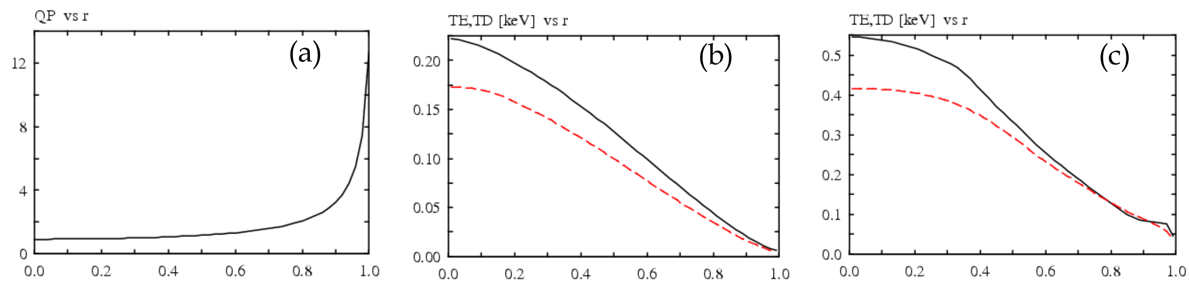

Figure 1. Results of equilibrium and transport calculations: q-profile (a), predicted temperature profiles in the Gyro-Bohm model (b) and the GLF23 model (c). TE and TD represent electron and ion temperatures, respectively.

4-2. Low Aspect ratio RFP plasmas

As for a low aspect ratio RFP with shaped magnetic surface and neoclassical effects, mechanism of the turbulent transport due to micro-instabilities such as ITG mode is not understood well. It is considered that its configuration has some different characters from the standard high aspect ratio RFP plasma.

The improvement of the TASK/EQ module has already allowed the computation of the low aspect ratio RFP equilibrium with a non-circular cross-section [5]. For the first application of the TASK/TR module to the RFP, it is considered that more basic models such as the classical Bohm or Gyro-Bohm model are passable as the anomalous transport model. For this reason, we implemented the fundamental Bohm diffusion model, and performed the verification calculation to examine the applicability of the TR module to the RFP configuration.
Here, we assumed the RFP equilibrium parameters at the same level as the ST plasma described above, except for the plasma current I_ϕ =0.15MA and hydrogen plasma is assumed.

Figure 2 shows the result of calculations: (a) q-profile of RFP, (b) total current density profile and its each component profile on the minor radius, (c) predicted pressure profiles by the TR transport module. Calculated electron and ion transport coefficients were almost comparable, and became the relatively flat profile. Therefore, it is considered that predicted temperatures (i.e. pressures) show relatively flat profile.

As for the turbulence transport analysis using the GLF23 model, it was found that further modification of the module is necessary for a characteristic of the RFP configuration having q=0 surface. It can be considered to analyze only the internal region of the plasma without the reversal region firstly.

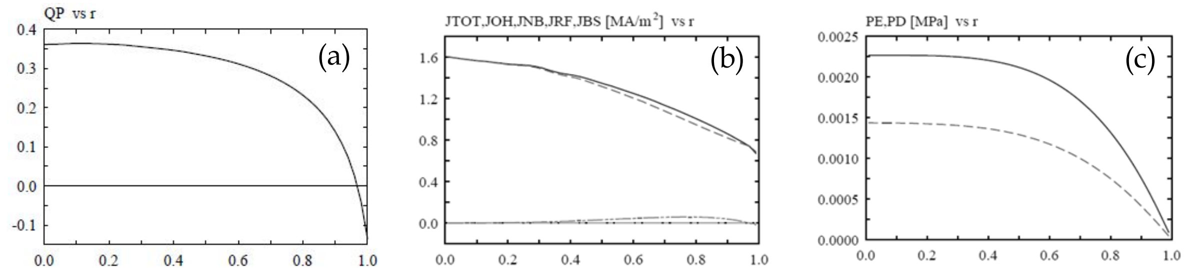

Figure 2. Results of the RFP transport calculation: (a) q-profile, (b) total current density profile, (c) predicted pressure profiles by the transport module.

5. Summary

We have investigated turbulence transport analysis in the low aspect ratio RFP configuration by using the TASK code. For the first application of TASK code to the RFP, some improvements were carried out to treat this configuration, such as the handling of normalized minor radius, expressions of some tokamak approximations about the magnetic field and current density. Also the classical Bohm diffusion model was implemented as a turbulence transport model, and preliminarily analyses were performed using the neoclassical and basic turbulent transport models for the RFP. For the Gyro-fluid transport model, transport calculation using the GLF23 model has enabled for the ST configuration. For the RFP, further modification of the module is necessary for the treatment of reversal region. It can be considered to analyze only the internal region firstly.

References

[1] Bruno A, *et al*., Physics of Plasmas **10**, 2330 (2003).
[2] Scheffel J and Schnack D D, Nuclear Fusion **40**, 1885 (2000).
[3] Predebon I, *et al*., Physics of Plasmas **17**, 012304 (2010).
[4] Fukuyama A, *et al*., J. Plasma Fusion Res. **81**, 747 (2005).
[5] Nagamine Y, *et al*., PLASMA 2011 Proceedings, 23P122-P (2011).
[6] Hayase K, *et al*., Proceedings of the 19th IAEA Fusion Energy Conference (Lyon France 2002)
[7] Escande D F, *et al*., Phys. Rev. Lett. 85, 1662 (1999)
[8] Masamune S, *et.al*., Journal of Fusion Energy 28, 187 (2009)
[9] Nagamine Y, *et al*., Proceedings of the 11th International Congress on Plasma Physics (Sydney Australia 2002)
[10] Shiina S, *et al*., J. Plasma Fusion Res. 81, 932 (2005)
[11] http://bpsi.nucleng.kyoto-u.ac.jp/bpsi/en/
[12] Dimits A, *et al*., Physics of Plasmas 7, 969 (2000).
[13] R.E. Waltz, *et al*., Physics of Plasmas 4, 2482 (1997).
[14] J.E. Kinsey, *et al*., Physics of Plasmas 12, 052503 (2005).