Diffusive Transport Analysis in Low Aspect Ratio Reversed Field Pinch

Yasuo Nagamine¹, Atsushi Fukuyama², Shoichi Shiina³ and Masamitsu Aizawa¹

¹ Institute of Quantum Science, Nihon University, Chiyoda-ku, Tokyo, Japan
² Department of Nuclear Engineering, Kyoto University, Sakyo-ku, Kyoto, Japan
³ National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan

E-mail: nagamine@phys.cst.nihon-u.ac.jp

Abstract. For the evaluation of confinement property of a low aspect ratio reversed field pinch (RFP) plasma, diffusive transport analysis is studied. Numerical analysis based on the neoclassical transport model in a low aspect ratio RFP show that a considerable bootstrap current contribution can be expected in this configuration, when incorporating the effects of non-circular cross-section and low aspect ratio. So-called neoclassical RFP equilibrium are also found to attain both high stability beta limit and high bootstrap current fraction. However, of transport phenomena in an RFP, the energy confinement time \( \tau_E \) might be determined by anomalous transport due to micro-instabilities. To analyze such transport phenomena in a low aspect ratio RFP, the applicability of the TASK (Transport Analysing System for TokamaK) simulation code are considered.

1. Introduction

In order to evaluate the confinement properties of a low aspect ratio (A) reversed field pinch (RFP) plasma, diffusive transport analysis is studied theoretically. In the conventional RFP plasma with larger aspect ratio, transport analysis by using the theoretical model or three-dimensional numerical simulations based on the cylinder approximation, has been shown to be nearly consistent with the present experimental results such as the confinement scaling[1,2]. On the other hand, confinement performance in a low aspect ratio RFP is not well understood, but it is considered to be important to introduce the transport model including the effect of toroidal geometry. Numerical analysis based on the neoclassical transport model in a low aspect ratio RFP show that a considerable bootstrap current contribution can be expected in the RFP configuration, when incorporating the effects of non-circular cross-section and low aspect ratio[3]. In Ref.[3], however, transport coefficients were evaluated by a simple model based on the collisionless approximation. Therefore, in present study we perform more precise analysis of transport coefficients based on the model applicable to all collisionality regimes. However, of transport phenomena in an RFP, the energy confinement time \( \tau_E \) might be determined by anomalous transport due to micro-instabilities. Therefore, it must be considered to select an appropriate model for the turbulent transport in the RFP configuration.

For numerical analysis of transport phenomena in a low aspect ratio RFP plasma, the applicability of the TASK (Transport Analysing System for TokamaK) simulation code[4] was considered. In TASK code, the code groups analyzing the physical processes such as equilibrium, transport, wave propagation, etc. are connected to calculate predictably the development as a whole. This code has
been developed for the tokamak and helical magnetic configurations. For analysis of an RFP, because of the different nature of the magnetic configuration, validation analysis of the applicability of the physical models implemented in TASK code is required.

2. Low aspect ratio RFP

In this section we consider some characteristic features of 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[5]. 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[6] with high beta. A helical structure has also been observed experimentally in A=2 RFP device[7].

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[8]. 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[9]. 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 code is open source codes, which are mainly developed at Kyoto University[4, 10]. This code consists of some modules listed in Table 1. In TASK code, the code groups analyzing the physical processes such as equilibrium, transport, wave propagation, etc. are connected to calculate predictably the development as a whole.

| EQ  | 2D Equilibrium | Fixed boundary, Toroidal rotation |
|-----|----------------|-----------------------------------|
| TR  | 1D Transport   | Diffusive Transport, Transport models |
| WR  | 3D Geom. Optics | EC, LH: Ray tracing, Beam tracing |
| WM  | 3D Full Wave   | IC, AW: Antenna excitation, Eigen mode |
| FP  | 3D Fokker-Planck | Relativistic, Bounce-averaged |
| DP  | Wave Dispersion | Local dielectric tensor, Arbitrary f(\epsilon) |
| PL  | Data Interface | Data conversion, Profile database |
| LIB | Libraries      |                                    |

EQ module solves the Grad-Shafranov equation which describes MHD equilibrium configurations of the axisymmetric toroidal plasma. As a numerical solution, the poloidal flux \( \psi(R,Z) \) in cylindrical coordinates is obtained for given pressure profile \( p(\psi) \) and parallel current density profile \( j_z(\psi) \), or safety factor profile \( q(\psi) \). TR module solves diffusive transport equations for the given geometry. Time evolutions of the spatial distribution of plasma density \( n(\rho) \), temperature \( T(\rho) \), current density \( j_z(\rho) \) etc are calculated based on a geometric factor \( \nu'(\rho) \), absorption power \( P_{abs}(\rho) \), externally driven current \( j_{ext}(\rho) \) and so on. Where \( \rho \) represents the normalized minor radius.
In TR module, some diffusive transport models based on the neoclassical transport theory and turbulent transport theory are implemented. In present study, applied for the first time to the RFP configuration, the code is exploited for steady state equilibrium calculations with the neoclassical transport model. It is useful to confirm the numerical results by comparing with previously obtained results in Ref.[3].

As the neoclassical transport model, Hinton & Hazeltine[11], Wilson(Hirshman-Sigmar)[12], Sauter[13] and NCLASS model[14] which was developed as a general numerical model for tokamak plasmas are considered in TASK code. NCLASS is a multi-species fluid model which calculates bootstrap current and neoclassical transport in tokamaks of arbitrary collisionality and aspect ratio. This model uses a recent formulation of the neoclassical plasma viscosity for arbitrary shape and aspect ratio (including the unity aspect ratio limit), arbitrary collisionality, and orbit squeezing from strong radial electric fields.

In order to include the description of the RFP geometry, some parts of the code need to be improved. As the most fundamental improvement, there is the taking of normalized minor radius $\rho$. In TASK code, this $\rho$ is defined by the square root of toroidal flux, i.e. $\rho = \sqrt{\psi/\psi_{\text{in}}}$, where $\psi_{\text{in}}$ represents the toroidal flux at plasma boundary. For the RFP configuration, however, since the toroidal field reversal occurs near the plasma boundary, the toroidal flux profile is not a monotonic function between the plasma center and edge. Therefor, $\rho$ cannot be used as a minor radius. For unified description of the tokamak and RFP configurations, the definition $\rho_p = \psi_p/\psi_{\text{po}}$ must be used as a normalized minor radius, where $\psi_p$ and $\psi_{\text{po}}$ represent the poloidal flux and its edge value, respectively.

4. Preliminary Results of TASK calculation
As preliminary calculations of TASK code, equilibrium analysis of low A RFP is performed by the modified EQ module. Figure. 1 shows the result of calculations: (a) magnetic surfaces, (b) toroidal and poloidal current density profiles on the midplane, (c) safety factor profile, in the case of parameters $A=2.0$, ellipticity $\kappa=1.4$, triangularity $\delta=0.4$, plasma current $I_p=0.15\text{MA}$ and parabolic pressure profile.

Figure 1. Equilibrium profiles calculated by EQ module: (a) magnetic surfaces, (b) toroidal and poloidal current density profiles on the midplane, (c) safety factor profile.

5. Considerations for turbulent transport analysis
In tokamaks, so many transport analysis 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[15].
As the turbulent transport model, CDBM (Current Diffusive Ballooning Mode)[16], GLF23[17], IFS/PPPL[18] and Weiland[19] models are employed in TASK code. The IFS/PPPL model is based on nonlinear gyro-fluid simulations, which predict the fluctuation and thermal transport characteristics of toroidal ion-temperature-gradient driven (ITG) turbulence, along with comprehensive linear gyro-kinetic ballooning calculations, which provide accurate growth rates, critical temperature gradients, and a quasilinear estimate of $\chi_e/\chi_i$. The Weiland ITG model is also based on a fluid description in which all moments that are driven by sources (i.e., fueling, heating) are included self-consistently. The fluid moments that are not driven by sources generally decay to zero. The model allows free energy exchange between different transport channels, leading to pinch fluxes. The transport coefficients are derived by using quasilinear theory and a mixing-length rule for saturation. The transport coefficients therefore have gyroBohm scaling. However, they have been found to agree well with some nongyro-Bohm L-mode and H-mode experimental data. The Weiland model also includes effects from the impurity profiles, fast ions, and $T_e \neq T_i$, and has been extended to include parallel ion motion and electromagnetic effects.

In order to explain quantitatively the anomalous transport observed for the experimental plasma in a turbulent state, it is necessary to solve the nonlinear gyro-kinetic equation for micro-instability modes including the nonlinear term associated with the convective $E \times B$ drift, where the particle distribution function and the fluctuation field in saturated turbulent state are calculated. In the gyro-kinetic simulation, however, a large amount of time and memory is required to calculate the distribution function in five dimensional phase space.

In the calculation of the gyro-fluid simulation and the gyro-kinetic simulation due to $\delta f$ method giving the base of IFS/PPPL model, however, the results for the saturated turbulence level and the anomalous transport coefficient are different each other even in the same condition on the simulation domain, etc. Generally the gyro-fluid simulation gives the larger anomalous transport coefficient than the gyro-kinetic simulation in present stage. The cause of these differences is still unresolved at present.

Recently, as for an RFP, linear gyro-kinetic calculations are applied to the RFP configuration to investigate the occurrence of ITG instabilities[20]. In Ref.[20], linear electrostatic calculations of ITG instability are performed by exploiting the GS2 numerical code[21], which is a widely known gyro-kinetic code based on the electromagnetic nonlinear gyro-kinetic equation. For the description of the RFP geometry, some parts of the code GS2 have been modified. Dependence of ITG instability threshold in different plasma conditions on the most relevant parameters such as the density gradient $-Rd \ln n/dr$ and the electron to ion temperature ratio $T_e/T_i$ was studied in the flux tube domain.

This analysis shows ITG modes are in general stable in RFP plasmas in the area of experimental parameters, and this type of instability to be only marginally responsible for particle and energy transport. The required gradients could be reached only in correspondence to the temperature slopes arising at the boundary of the helical structure in QSH states. It is also shown the Landau damping effect resulting from the shorter connection length of the RFP is an important vehicle to suppress ITG turbulence. I.e. a quenching of the wave-particle interaction implies a quick increase in the ITG growth rate. It is also reported that the ITG instability threshold remains quite high about five times at midradius as compared with a tokamak plasma.

Numerical calculations in Ref.[20], however, are based on geometry and parameters of the RFX experimental device with aspect ratio $R/a \approx 4$. Also some geometric simplifications such as circular surfaces with no shift and so on are imposed although toroidicity is kept into account. As for an low aspect ratio RFP with shaped magnetic surface and neoclassical effects, understanding the mechanism of transport is considered to be an interesting subject, for its configuratin has some different characters from the standard high aspect ratio RFP plasma.
6. Summary
In TASK code, several turbulent transport models are implemented as mentioned above. However, this code has been developed for the tokamak and (recently) helical magnetic configurations. For analysis of an low A RFP, because of the different nature of the magnetic configuration, some modifications and validation analysis of the applicability of the physical models in TASK code are required.

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