TRANSPORT SIMULATION OF EAST LONG PULSE DISCHARGE AND HIGH BETAN DISCHARGE WITH INTEGRATED MODELLING

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Abstract

In the past two years, two major scenarios were developed on the EAST tokamak, the long pulse steady state scenario and the high βN scenario. For the steady state scenario, 100 s long pulse discharge was achieved with only radio frequency heating and current drive (CD) and it has improved confinement with H98~1.1. For the high βN scenario, the βN ~2.0 was sustained for ~2 s, with an internal transport barrier (ITB) in all channels. Under OMFIT framework, a workflow was developed to simulate the two scenarios on EAST. The workflow integrated the equilibrium code EFIT, transport code TGYRO for energy transport, transport code ONETWO for current evolution and radiation, heating and CD code GENARY/TORAY/NUBEAM for driven current and energy sources. For long pulse discharge, the integrated modelling well reproduced the experimental electron and ion temperature profiles and current (or q) profiles. This validated our integrated modelling workflow and validated the TGLF transport model for the scenario possessing dominant electron heating and low torque. The modelling also gives the physical picture of the improved confinement induced by the on-axis ECH: the on-axis ECH increased the central electron temperature, make the LHCD power deposit to inner region and make the current profile more peaked, which suppress the high-k micro-instabilities at the core region and improve the confinement. The integrated modelling workflow also was used for the high βN discharge of EAST. However, it could not reproduce the experimental temperature profiles. The possible reason is the fishbone instability appeared in the discharge, which could redistribute the fast ion and affect the energy transport. M3D-K MHD code was used to simulate the fishbone activity and we do see the heat flux caused by fishbone.

1. INTRODUCTION

One major mission of EAST is to demonstrate the operation scenarios to support the ITER and the Chinese Fusion Engineering Test Reactor (CFETR). As a super conducting tokamak, EAST could demonstrate the real steady state scenario with the pulse length much longer than the current diffusion time. EAST also has some unique features such as RF heating and electron heating dominant, low torque, active water-cooler tungsten divertor. With these features EAST could make unique contributions to the magnetic fusion community. In the past two years, two major scenarios were developed on the EAST tokamak. One is the long pulse steady state scenario [1], the other is the high βN scenario [2]. For the steady state discharge, 100 seconds long pulse discharge has been achieved with only radio frequency (RF) heating and current drive (CD) and it has improved confinement with H98~1.1. For the high βN scenario, the βN=2.0 was sustained for ~2 s, with an internal transport barrier (ITB) in all channels.

To project the scenarios to ITER and CFETR, one physics-based method is to perform the transport simulation. Generally, this is done by integrated modelling transport code. In the magnetic fusion community, a lot of transport codes has been developed, such as ONETWO, TRANSP, ASTRA, JETTO and TOPICS. Recently, under the OMFIT integrated modeling framework [3], we developed a workflow for transport simulation to
include ONETWO, TGYRO/TGLF/NEO and EFIT modules [4,5]. However, before the models are used to predict the ITER or CFETR scenarios, it should be validated by today’s tokamak experiments. The two scenarios on EAST provided good test cases for the steady-state and hybrid scenarios. If the models could reproduce the experiments, then we have the confidence to use the integrated modeling tools to predict EAST experiments and ITER/CFETR scenarios. The transport simulation also helps us to analyze the experiments and deeply understand the physics behind the scenarios, e.g., what the current components are, why the confinement is improved.

The paper is organized as follows. Section 2 describes the long pulse steady state scenario and the hybrid-like high $\beta_N$ scenario on EAST. In Section 3, first we explain the OMFIT workflow used for transport simulation, then in 3.2 and 3.3 we use the workflow to simulate the two scenarios, respectively, discuss the validation and the physics behind the scenarios. Finally, section 4 summarizes the results and discusses the application of the workflow to predict CFETR operation scenarios.

2. LONG PULSE STEADY STATE DISCHARGE AND HIGH BETAN DISCHARGE

EAST has achieved the 100 s steady state long-pulse discharge, which is a world record pulse length for H-mode plasma. The time trace of the plasma parameters and key profiles are shown in Fig. 1. It is upper single null tungsten divertor configuration. The major parameters of the discharge are: $B_{t0} = 2.5$ T, $I_p = 400$ kA, $q_{95} = 6.7$, $<n_e> = 3.0 \times 10^{19}/m^3$, $\beta_N = 1.0$, and $\beta_p = 1.2$. The heating scheme is: $1.7$ MW $4.6$ GHz LHW, $0.53$ MW $2.45$ GHz LHW, $0.3$ MW ECRH and $0.4$ MW ICRH. The $q$ profile is central flat with $q(0) \sim 1.5$, as shown in Fig. 4(a). The $q$ profile is reconstructed by EFIT with the constraint of the Faraday rotation angle measured by far-infrared polarimeter interferometer (POINT) [6]. This discharge has a weak ITB at the central region, and the confinement is improved with $H98 \sim 1.1$. the kinetic profiles are shown in Fig. 4. Later this scenario was extended to higher density, more input power and better confinement (See OV/2-2 in this conference).

EAST also achieved the hybrid-like high $\beta_N$ discharge. In this scenario, the toroidal field is set to $1.5$--$1.6$ T, $q_{95} = 3.4$--$4.4$, $I_p = 400$--$500$ kA, $<n_e> = 3.0$--$5.5 \times 10^{19}/m^3$, $\beta_N = 1.5$--$2.1$, $H98 = 0.9$--$1.1$. The main heating power is NBI and LHW. in this scenario, ITBs in all channels are often observed [2, 7]. Abundant MHD activities appears, including sawtooth, fishbone and reversed shear Alfvén eigenmodes (RSAE). The corresponding $q$ profiles are monotonic $q$, flat central $q$ and reversed $q$, which are confirmed by EFIT reconstruction. The relationship between the ITBs and MHD activities is still under investigation. Fig. 2 shows the time trace of a typical discharge 71320. The NBI power is $4.0$ MW and $4.6$ GHz LHW power is $1.0$ MW. For the discharge, $\beta_N \sim 1.9$ with ITB was maintained for about $2$ s. The reconstructed $q$ profile shows it has a central flat $q$ and fishbone MHD activity was observed, as shown in Fig. 2(f).

**FIG. 1. Time trance of 100 s long pulse steady-state discharge.**
3. TRANSPORT SIMULATION

3.1. OMFIT workflow for transport simulation

Under the OMFIT integrated modeling framework, we developed a workflow for transport simulation, as shown in figure 3. The workflow integrates EFIT [8], TGYRO [9] and ONETWO [10]. EFIT is a robust equilibrium solver for equilibrium reconstruction and construction. Here in the prediction simulation, only the construction method is used. TGYRO is a transport equations solver for stationary state, it integrated GYRO [11], TGLF [12] and NEO [13] transport model. Both GYRO and TGLF are turbulence transport model. GYRO is too tedious, so TGLF is used in our transport simulation. TGLF is the state-of-the-art turbulence transport model, solvers the gyro-Landau-Fluid equations to calculate the heat flux, energy flux and momentum flux. It has been
validated by many experiment cases [14] and is keeping actively updating. NEO is an advanced neoclassical transport model by solving the drift-kinetic equations. For given sources, TGYRO could calculate the density, temperature and toroidal rotation profiles of stationary state. ONETWO itself is an integrated transport simulation code to solve the transport equations of density, temperature, momentum and current density. It integrates all kinds of heating and CD modules to calculate the sources. Here the heating and CD modules include NUBEAM for NBI, GENRAY/CQL3D for LHW and TORAY-GA for ECH. ONETWO also integrated various transport models and equilibrium solvers. However, in this workflow, ONETWO is only used to evolve the current and calculate the sources, since the TGYRO is much faster for stationary state and the advanced TGLF/NEO transport models are not integrated into ONETWO. Since the time scale of energy diffusion and current diffusion are quite different, the ONETWO and TGYRO could run separately.

The iteration steps of the workflow are described as follows:

(1) Starting from an experimental initial state at time \( t_0 \) during flat top. The initial state includes the equilibrium and kinetic profiles such as electron density, electron temperature, ion temperature, rotation, radiation and effective heat source from TORIC.

(2) Keeping the kinetic profiles and the plasma current \( I_p \) fixed, ONETWO calculates the energy sources and sinks and evolves the plasma current density with the external current drive calculation by the RF codes for time step \( \tau \) from \( t_0 \) to \( t_0 + \tau \). For the EAST long-pulse H-mode discharges, the time step is set to 0.1 s since the temperature profiles did not change much within 0.1 s in the integrated modeling.

(3) At the end of step (2), EFIT calculate the updated equilibrium with the \( P' \) (pressure gradient) and \( FF' \) (poloidal current gradient) outputted from ONETWO.

(4) Using the sources and sinks from step (2) and the updated equilibrium from step (2), TGYRO calculated the electron and ion temperature profiles in the core region at time \( t_0 + \tau \).

(5) The new core temperature profile from step (4) and the boundary temperature profile at \( t_0 + \tau \) from the experiment are combined to form an updated temperature profile valid for all \( \rho \). The new temperature profiles are mapped into the equilibrium \( (P') \) from step (3).

(6) The updated temperature profiles and equilibrium from step (5) serve as input to ONETWO and the next time advancement begins starting with step (2). The process from step (2) to step (6) is repeated \( N \) times to \( t_N = (t_0 + N\tau) \) to obtain a time-dependent simulation of tokamak plasma to get a steady-state.

There are still some limitations in our transport simulation: (1) Only the current profile, electron temperature profile and ion temperature profile are simulated. The density profile and momentum profile are fixed as experiments. Because the particle source is very hard to get, and the transport of particle and momentum are still great challenge. (2) We only evolve the core region of temperature profile (generally \( \rho < \rho_{\text{edge}} - 0.8 \)), because at present there is no mature transport theory in pedestal and pedestal top region.

Before the workflow is used for prediction, it should be validated by existing experiments. Also, some modules in the integrated modeling should be validated. In the transport simulation, two kinds of key element are still in challenge and should be validated in some cases. One is the transport model, the other is the heating/CD model for sources. For the transport model TGLF; it has been validated for many cases, even ITB case [14]. However, for the electron heating dominant and low rotation, it still need to be validated. For heating/CD models, NUBEAM for NBI and TORAY-GA for ECRH are relatively mature, but the GENRAY-CQL3D for LHW still need to be validated. In next section, we use EAST experiments to test the models. As mentioned in introduction, these EAST experiments have some unique features related to fusion reactor, they are good test cases for the models in the integrated simulation.

### 3.2. Simulation for the long-pulse discharge

Using the workflow described in section 3.1, first we simulate the long pulse discharge. Here the discharge 66740 is selected. It is a 32 s long pulse, has similar parameters to the 100 s discharge. But 66740 has relatively good measurement data. It has a small power of ICRH. Because the ICRH modules in ONETWO are out of date, we use the standalone TORIC code to calculate ICRH. At initial step the heat source from TORIC is calculated, then it is fixed for the whole simulation. In the following subsection we will see the ICRH has small power deposition and it has litter effect on the whole transport simulation.

#### 3.2.1. Validation of models and transport analysis
The simulation time duration is 14.0 s – 18.0 s. During this time the plasma is at a stationary state and all the parameters are almost unchanged. The calculated current density profiles of each current component are shown in Fig. 4(b). We can see that the simulated total current density profile qualitatively agrees with experimental current density profile, which is reconstructed by EFIT with the constraint of POINT. The bootstrap current fraction is ~28%, the LHW fraction is ~71%, the ECCD fraction is ~2% and the ohmic current is ~1%. The calculated ohmic current is a small negative fraction, while the experimental loop voltage is a small positive number (~0.02 V), we think this is due to the bootstrap current or LHCD is a little over calculated. Anyway, the calculated total ohmic current is negligible, which agrees with the experiment. The agreement of ohmic current and total current density profile validates the current driven models in the transport simulation, i.e., the GENRAY-CQL3D models are validated for LHCD calculation in H-mode plasma.

**FIG. 4.** Profiles of discharge 66740 at 14 s. (a) experimental q profile, reconstructed by EFIT with POINT constraint. (b) Current density profiles of each component. The brown line is the experimental current profile corresponding the q profile in (a), other profiles are calculated by the workflow. (c) Profiles of power deposition to electron. (d) Profiles of power deposition to ion. (e) Electron temperature profile from experiment and from simulation. (f) Ion temperature profile from experiment and from simulation.

Fig. 4(c)-(d) gives the calculated power deposition to electron and to ion. The power is almost all to electron at the central region, only ICRH has small power to ion. Fig. 4(e)-(f) show that the simulated temperature profiles agree well with the experimental profiles. This validates the TGLF model for the case of low torque and electron heating dominant.

**FIG. 5.** Profiles of discharge 66744 before and after the ECH turned off at 4.0 s. (a) Experimental electron temperature profile. (b) LHCD current density profiles calculated by GENRAY-CQL3D.

Experiments show 0.3 MW ECH play an import role for the confinement improvement. Actually, there is a discharge 66744 similar to 66740, except the ECH is switched off at time t = 4.0 s. After the ECH switched off,
the electron temperature drops obviously (Fig. 5(a)), the stored energy decreases from 140 kJ to 110 kJ, and H98 drops from 1.0 to 0.8. We calculate the LHCD current profile before and after the ECH switched off, respectively, as shown in Fig. 5(b). It shows that with ECH on, the LHCD deposition location will move more inside. The reason is straightforward: on-axis ECH could increase the electron temperature at central region, which makes LHCD deposition location further inside. The next question is why the confinement is improved? When the LHCD deposition location changes, both the heat source and current profile change, then which is the cause of improved confinement? To answer this question, we made test simulations: fix the current profile and change the heat source, or fix the heat source and change the current profile. Our simulation shows that the more peaked current density profile contributes ~2/3 improved confinement, while the more on-axis heat source from LHW contributes ~1/3. Further micro instability analysis is carried out by the TGLF, shows that the peak current density profile could suppress the high-k micro-instabilities at the central region, leads to weak ITB and improved confinement.

3.2.2. Prediction for various ECH conditions

In the EAST steady-state scenario, a small ECH power could lead to improved confinement. Then the question is if we change the ECH condition, can we further improve the confinement and achieve higher plasma performance? To answer the question, we tried to scan the ECH parameters. What we can change is the power and injection angle. Actually, in 2017 EAST only had one gyrotron and the ECH power is 0.3 MW ~ 0.5 MW. In 2018 one more gyrotron was installed. We would like to know the plasma performance with increasing the ECH power. Unfortunately, our simulation shows that for the steady-state scenario like 66740, more 0.3 MW ECH could only increase the stored energy from 150 kJ to 155 kJ (~3%). We also scan the ECH power deposition locations, by varying the poloidal launch angle, and run the transport simulation. The corresponding ECCD, LHCD, electron and ion temperature profiles are shown in Fig. 6. We can see that the on-axis ECH is the best case, the stored energy is 30% higher than the worst case.

FIG. 6. Scan the ECH power deposition location by varying the poloidal launch angle. (a) ECCD current density profiles. (b) LHCD current density profiles. (c) Simulated electron temperature profiles. (d) Simulated ion temperature profiles.

In summary, ECH and LHW have strong synergy effect. On-axis ECH and peak current density profile is good to confinement. The physics picture of improved confinement is: the on-axis ECH increased the central electron temperature, make the LHCD power deposit to inner region and make the current profile more peaked, which suppress the high-k micro-instabilities at the core region and improve the confinement.

3.3. Simulation for the high $\beta_N$ discharge

The transport simulation was also performed for the high $\beta_N$ discharge, using the same workflow as in section 3.2. Fig. 7(a) shows the experimental q profile and thermal pressure profiles. Fig. 7(b) gives the current density profiles of each components, which are calculated by ONETWO. The current fractions are: ohmic current 60%,
bootstrap current 21%, LHCD current 9% and NBCD current 10%. The ohmic current is still the major component, and the q profile is central flat, so we call it a hybrid-like scenario. The simulation evolves the profiles to t = 6.0, when the plasma reached at a relatively stationary state. Fig 7(c) compares the simulated and the experimental temperature profile at time 6.0 s. We can see the simulation cannot agree with the experiments, and the ITB structure cannot be reproduced. We think the cause may be the fishbone activity in the central region. Fishbone may affect the transport process of background plasma, but the TGLF transport model does not include the physics. Actually, the MHD code M3D-K has been used to simulate the fishbone activity of this discharge and we do see the heat flux induced by fishbone. Further work need to include the heat flux into the transport simulation to see the fishbone effect.

FIG. 7. Profiles of 71320 at 6.0 s. (a) Experimental q profile and thermal pressure profiles. (b) Current density profiles of each component, calculated by ONETWO. (c) Ion temperature profile from experiment and from simulation.

4. SUMMARY

In summary, under the OMFIT framework, we developed a workflow for transport simulation to integrate the ONETWO, TGYRO/TGLF/NEO and EFIT. The workflow, the therein TGLF transport model and GENRAY-CQL3D heating/CD module are validated by the EAST long-pulse steady state discharge. The simulation also helps us to understand the scenario: on-axis ECH and LHW have strong synergy effect, the on-axis ECH increased the central electron temperature, make the LHCD power deposit to inner region and make the current profile more peaked, which suppress the high-k micro-instabilities at the core region and improve the confinement. However, for the hybrid-like scenario, the transport simulation cannot reproduce the experimental profiles. We think the cause may be the fishbone activity in the central region. Further work need to include the heat flux induced by fishbone into the transport simulation to see the fishbone effect.

The workflow and the transport model have been validated for the EAST steady-state scenario. This enhance our confidence to use the workflow to predict the CFETR steady-state scenario. A similar workflow has been used for CFETR scenario design [4]. The workflow for CFETR is even more complicate: the EPED model is coupled in the workflow to determine the profiles at pedestal region. However, more validation work is needed for fusion reactor related experiments.

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