Experimental progress of hybrid operational scenario on EAST tokamak

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Abstract
Extensive experiments of advanced scenario development, which contribute to the ITER hybrid operational scenario have been carried out on experimental advanced superconducting tokamak (EAST) tokamak recently with the ITER-like tungsten divertor. The $\beta_N$ in this operational scenario is intermediate up to 2.1 (EAST#78987, $\beta_N \sim 2.1$, $I_p \sim 0.45$ MA, $q_{95} = 3.7$, $B_T \sim 1.5$ T, 3 MW neutron beam injection and 1 MW 4.6 GHz lower hybrid wave). In these hybrid H-mode plasmas, the internal transport barrier (ITB) has been frequently observed with central flat $q$ profile and it is found that the fishbone mode ($m/n = 1/1$) can be beneficial to sustain the central flat ($q(0) \sim 1$) $q$ profile, thus a stable ITB can be obtained. In this case, better plasma performance is achieved. The formation of the ITB of the electron density is related to the fishbone activities. Energy transport analysis shows that the fishbone instabilities have a suppression on electron turbulent energy transport, while the ITB of ion temperature is due to the suppression of high-k modes (electron temperature gradient). The mechanism of turbulence suppression from fishbone instabilities in the EAST tokamak is not clear and needs more investigation. It is also observed that the power threshold for ITB formation is $\geq 3.5$ MW, which is consistent with the scaling law for other tokamaks. The dimensionless parameter $G (= H_{ff}/\beta_N^2/q_{95}^2)$ obtained in the EAST reaches 0.3, but is still lower than the ITER hybrid scenario design ($G \geq 0.4$) and needs more extension. Further investigation of extending the operational regimes, such as expanding the ITB foot outwards, would be important for the development of the hybrid and steady-state scenarios for next-step fusion devices like ITER and CFETR.

Keywords: EAST, high normalized beta, fishbone, power threshold

(Some figures may appear in color only in the online journal)

1. Introduction

The achievement of steady-state operation with high performance is one of the major challenges for present day tokamaks and future fusion devices, like ITER [1] and CFETR [2]. The steady-state operation of ITER will be the full non-inductive current-driven plasma with a pulse length of 3000 s due to engineering limit. The demonstration of steady-state scenario on current tokamaks [3–14] needs a simultaneous integration of engineering technology and physical issues, such as external current drive, heat flux to the first wall and divertor, and active plasma control. The ITER hybrid scenario is considered as an intermediate step between the inductive
scenario and steady-state scenario [15, 16]. To support the prediction of the ITER hybrid scenario, different plasma operation modes have been developed in various tokamaks over the past two decades, such as JET [17], JT-60U [18], ASDEX-U [19] and DIII-D [20, 21].

The experimental advanced superconducting tokamak (EAST) [22–24] is an ITER-like fully superconducting tokamak facility and the mission of EAST (major radius $R \leq 1.9\text{ m}$, minor radius $a \leq 0.45\text{ m}$, plasma current $I_p \leq 1\text{ MA}$) is to demonstrate high plasma beta, high bootstrap current fraction, long-pulse, non-inductive scenario with metal walls, low momentum input and electron-dominated heating scheme. In the past few years, steady-state long-pulse operation has been achieved by using radio frequency (RF) heating and current drive on EAST [25–28]. A first demonstration of an over 100 s timescale long-pulse steady-state scenario has been successfully achieved on EAST, with good plasma performance ($H_{\text{95\%}} \sim 1.1$) and reliable control of impurity and heat exhaust with the tungsten divertor [25]. More recently, the operational regime has been extended to higher confinement quality with the bootstrap current fraction up to $\sim 50\%$ and $\beta_p$ up to 1.9 [28]. Besides, in order to contribute to the ITER hybrid operational scenario, the hybrid plasma was developed on EAST by neutron beam injection (NBI) and lower hybrid wave (LHW) heating since the 2015 EAST experimental campaign [29]. In this scenario, the internal transport barrier (ITB) has been observed in profiles of ion temperature, electron temperature and electron density within $\rho < 0.5$ [30] and it is different with the EAST steady-state scenario, where only the electron temperature ITB was observed and the ion temperature profile was much lower than the electron temperature profile [28]. Sustained high normalized beta ($\beta_N \sim 1.9$) plasmas with an ITER-like tungsten divertor have been achieved on EAST tokamak with a flat central $q$ profile ($q(0) \sim 1$) recently [31]. The fraction of non-inductive current is about 40% [31]. The high $\beta_N$ scenario developed on EAST will provide an important test bed to address some key physics for the hybrid scenario for next-step fusion devices such as ITER and CFETR.

In this paper, recent experimental progress of the hybrid plasmas on EAST tokamak is presented. The remainder of this paper is organized as follows. The development of advanced plasmas, which are good candidates for the hybrid scenario, is presented in section 2 with an ITER-like tungsten divertor. Energy transport analysis in the EAST with fishbone activities was done and shown in section 3. In section 4, power threshold of ITB formation in the EAST will be introduced. Discussion and summary are presented in section 5.

2. Development of hybrid operational scenario in EAST

2.1. Operational regime extension of H-mode plasmas with ITB

The long-pulse high $\beta_N$ operation will be an important task for hybrid scenario development on EAST. Analysis of the
experimental limit of $\beta_N$ has revealed several main features of typical discharges in the 2015 EAST campaign [29]. First, efficient, stable high heating power is required. Second, the control of impurity radiation (partly due to interaction between the plasma and in-vessel components) is also a critical issue for the maintenance of high $\beta_N$ discharges. In addition, ITB dynamics is another key issue for high $\beta_N$ plasmas. In EAST, the plasma-facing components are the molybdenum wall in the main chamber, lower divertor covered with graphite tiles and upper divertor covered with ITER-like W/Cu mono-block. As shown in [29], a lower single null divertor configuration is applied in the experiments in 2015. The upper divertor on EAST is a prototyping tungsten divertor for ITER, i.e. a water-cooled tungsten divertor with power handling capability of $\sim$10 MW m$^{-2}$ based upon cassette and monoblock technology. As shown in figure 3(c), an upper single null divertor configuration is applied in recent experiments. A fast CCD camera (visible wavelength) image is shown in figure 1 from $^*t = 3$ s to $^*t = 6$ s for the EAST discharge 80496($I_p \sim 0.45$ MA, $q_{95} = 3.7$, $B_T \sim 1.6$ T), and no frequent impurity spark-like events were observed. This means that there are no strong plasma–material interactions with an ITER-like tungsten divertor. The fusion gain is proportional to the normalized beta ($\beta_N$) with certain conditions and the dimensionless parameter $G = H_{89}/\beta_N q_{95}^2$ is a conventional dimensionless quantity to evaluate the plasma fusion performance [32]. In order to explore the high $\beta_N$ and high $G$ operational regime, extensive experiments of hybrid scenario development have been carried out on EAST ($I_p = 400–500$ kA, $B_T = 1.5–1.6$ T, $q_{95} = 3.4–4.4$) with the ITER-like tungsten divertor in 2018 and 2019. The max $\beta_N$ increases from 1.9 (EAST#71320, $\beta_N \sim 1.9$, $I_p \sim 0.4$ MA, $q_{95} = 4.7$, $B_T \sim 1.6$ T, 4.8 MW NBI and 1 MW 4.6 GHz LHW) to 2.1 (EAST#78987, $\beta_N \sim 2.1$, $I_p \sim 0.45$ MA, $q_{95} = 3.7$, $B_T \sim 1.5$ T, 3 MW NBI and 1 MW 4.6 GHz LHW). The $G$ value is promoted from 0.13 (EAST#71320, $\beta_N \sim 1.9$, $H_{89} \sim 1.5$, $q_{95} \sim 4.7$) to 0.3 (EAST#78977, $\beta_N \sim 1.9$, $H_{89} \sim 2.2$, $q_{95} \sim 3.7$). Although significant promotion of the $G$ value has been achieved in the EAST high $\beta_N$ plasmas, it is still lower than the ITER hybrid scenario design ($G \geq 0.4$) [1] and needs more extension. Besides the operational regime extension, it is important to maintain high performance for long-pulse operation. Figure 2 shows the time traces of the EAST hybrid discharge 80496 ($\beta_N \sim 1.8$ for 4–6 s, $I_p \sim 0.45$ MA, $q_{95} = 3.7$, $B_T \sim 1.6$ T, and no frequent impurity spark-like events were observed). The safety factor profiles, electron density profiles and plasma shape for EAST H-mode discharge 80496 with ITER-like tungsten divertor configuration are shown in figure 3. The $\beta_N$ is sustained for 2 s at 1.8 with the ITB and the preset duration of the flat-top phase is required by the engineering issue of the NBI heating system. It is found that for H-mode discharge 80496 with the ITB phase at $t = 5$ s, the central $q$ profile is flat and $q \sim 1$ inside $\rho < 0.3$. Figure 4 shows the electron density gradient from far IR laser-based POLarimeter-INTerferometer (POINT) [33] and the wavelet spectrum from soft x-ray (SXR) diagnostics.


2.2. Optimization of safety factor profile in the EAST hybrid plasmas

The long-pulse high $\beta_N$ operation is attractive on EAST device and it is found that sustaining an optimized $q$ profile is one of the key factors for high-performance long-pulse operation from section 2.1. Three different $q$ profiles with high performances are observed in the EAST hybrid H-mode discharges (figure 5) with similar heating power scheme. One is a monotonic $q$ profile with sawtooth [EAST#71318] and the value of $\beta_N (1.6)$ is lower than #71320’s ($\beta_N = 1.9$), which has a flat central $q$ profile with fishbone instabilities. These two types of discharges can be sustained with high $\beta_N$ value. The last case has a reversed $q$ profile and the maximum $\beta_N$ can also reach 1.9 [EAST#71326].

Since the high $\beta_N$ operation is attractive for long-pulse operation, sustained hybrid discharges with sawtooth and fishbone instabilities have been studied and compared on EAST. Table 1 shows the parameters of EAST discharge 71318 and 78723. The $\beta_N$ (71318, $\beta_N \sim 1.6$; 78723, $\beta_N \sim 1.9$) flat-top phases are sustained at about 2 s in these two discharges. The injected heating power is nearly identical ($\sim 5.0$ MW). Comparisons of the electron temperature profile, ion temperature profile and electron density profile are presented in figure 6. It is observed that the EAST discharge 78723 has steeper and higher electron and ion temperature profiles. Also, an ITB is observed in electron density for 78723, but a flat density profile for the sawtooth case. The difference in the $\beta_N$ values should be due to the discrepancy between the kinetic profiles for discharge 71318 and 78723. The increase of the gradient for the kinetic profile also leads to the increase of non-inductive current fraction ($24\%\rightarrow 42\%$). Further transport analysis (section 3) shows that fishbone instability suppresses electron turbulent transport, while the ITB in the ion temperature channel is due to the suppression of high-k modes (electron temperature gradient (ETG)).

By ramping up the plasma current, the transfer from the monotonic $q$ profile to the central flat $q(0) \sim 1$ profile has been achieved. For instance, in EAST #71319 [31], before the current ramp-up, a central flat $q(0) \sim 1$ profile with fishbone ($m/n = 1/1$) core instability similar to #78723 is observed. The current ramp-up is set from $t = 5$ s, $I_p = 400$ kA to $t = 6$ s, $I_p = 450$ kA. The transfer from fishbone to sawtooth instability with a reversal surface of $q(\rho) = 1$ at $\rho = 0.3$ occurred at $t = 5.5$ s. The sustainment of the ITB in the electron density

![Figure 4. Electron density gradient contour plot and the $m/n = 1/1$ fishbone analysis from SXR diagnostics for EAST discharge 80496.](image)

![Figure 5. Three types of EAST H-mode discharges with different $q$ profiles: black, #71318, monotonic $q$ profile with $q_{\text{lim}} < 1$; red, #71320, central flat $q$ profile with $q(0) \sim 1$; blue, #71326, reverse-sheared $q$ profile with $q_{\text{lim}} < 2$.](image)

| Shot | 71318 | 78723 |
|------|-------|-------|
| $I_p$ (MA) | 0.4 | 0.43 |
| LHW + NBI (MW) | 5.0 | 5.1 |
| $\beta_N$ | 1.6 | 1.9 |
| $<n_e>$ ($10^{19}$ m$^{-3}$) | 3.5 | 3.8 |
| Non-inductive current fraction | 24% | 42% |
| MHD | Sawtooth | Fishbone |

Table 1. Comparisons of parameters for sustained hybrid discharges with sawtooth and fishbone instabilities.
channel is accompanied with $m/n = 1/1$ fishbone instabilities, while the ITB disappears with the transformation from fishbone to sawtooth. This confirms again that the ITB of electron density is related to the fishbone activities. The change in plasma current leads to a change in $q_{95}$ from 4.6 to 4. With value $q_{95}$ near 4.6, sustained hybrid discharges with central flat $q(q(0) \sim 1)$ profile and fishbone instability have been reproduced robustly. The $q$ profile is clamped by fishbone instability ($m/n = 1/1$). The plasma particle and heat are exhausted outwards with the fishbone in a subtle way so the ITB plasma can be sustained.

Besides the transfer from fishbone to sawtooth, another $q$ profile has been observed with $q_{95} = 4$. This is also the third case in figure 5, the reverse-sheared $q$ profile with reverse-sheared Alfvén eigenmode (RSAE) instabilities. In this case, the $\beta_N$ value is not sustained and observed to crash down in a short timescale. It has been found that the degradation is related to the core magnetohydrodynamic (MHD) behavior (double tearing mode) [34]. In this case, RSAEs have been observed during the ITB formation before the crash [35]. It seems that the RSAEs cannot contribute to maintaining the ITBs.

Figure 6. Comparisons of electron temperature profile (a), ion temperature profile (b) and electron density profile for discharge 71318 at $t = 4.5$ s and 78723 at $t = 4.1$ s.

Figure 7. Plasma normalized betas verse different $q$ profiles and MHD instabilities, in conjunction with figure 5. Data for #71319 shows the transformation from the fishbone case to sawtooth case.

Figure 7 summarizes the experimental plasma $\beta_N$ with three $q$ profiles in this scenario. With the same heating scheme, the monotonic $q$ profile ($q_{\text{min}} < 1$) with repeated sawtooth leads to
3. Energy transport analysis in the EAST hybrid plasmas

The observed improvement and sustainment in the EAST hybrid plasmas with fishbone instabilities is quite interesting. A modeling work is done in this section to investigate the effect of fishbone activities on energy transport. As is well known, the cross-field transport in the tokamak plasmas generally exceeds the neoclassical predictions. It is commonly accepted that most of the transport in the tokamak plasmas is driven by plasma turbulence. The turbulent transport is mainly produced by micro-instabilities including, but not limited to, ion temperature gradient (ITG)-driven modes, trapped electron modes (TEMs) and ETG-driven modes. Transport code TGLF [36–39] is widely used to analyze and predict the turbulent transport in the tokamak plasmas [40–46]. The first-principles model NEO [47–49] is an accurate numerical solver of the drift-kinetic equation and computes the neoclassical transport flux. TGLF + NEO has proven to be an accurate predictive theory-based transport model for the core of L-mode, H-mode inductive discharges and DIII-D hybrid regimes [40–42, 50]. In addition, a few works have been done with TGLF + NEO on EAST steady-state discharges [51, 52]. TGYRO [53, 54], which utilizes TGLF for turbulent transport and NEO for neoclassical transport, is used in the present modeling work. The experimental energy sources and sinks including auxiliary heating and radiation loss and the energy exchange between the ions and electrons are calculated by ONETWO [55] transport code. The ray-tracing code GENRAY [56] and the Monte Carlo code NUBEAM [57] are used for LHW and NBI heating and current drive calculation.

For TGLF, three models named SAT0 [42], SAT1 [58], VX [59] are developed and applied for experimental prediction. The TGLF_VX model, developed by Xiang Jian and applied to the TGLF turbulence transport model, is aimed at capturing the physics of interaction between low-k and high-k turbulence consistent with the multi-scale gyro-kinetic simulation result reported by Howard [60] and it is more consistent with the experiment when high-k turbulence dominated. These three TGLF models are applied in predicting the electron and ion temperature profile for EAST discharge 71320 at $t = 2.6$ s. It is found that the VX model matches the experimental profiles best, as shown in figure 8. The $k$ spectrum of the linear growth rate and frequency of the most unstable modes from TGLF is shown in figure 9 ($\rho \sim 0.39$) for discharge 71320 at $t = 2.6$ s. The system of units used is $c_s = \sqrt{T_e/m_e} = c_s/\Omega_s\Omega_e$.
The normalized growth rate, frequency and poloidal wave number are $\gamma' = \gamma (a/c_s)$, $\omega' = \omega (a/c_s)$ and $k_y = \rho_s k_B$. The length scale $a$ is the circular equivalent minor radius of the last closed flux surface. Linear analysis shows that the high-$k$ ($k_y > 1$) mode’s instability (ETG) is stronger than the low-$k$ ($k_y < 1$) mode’s instability (ITG). This is consistent with the prediction, since high-$k$ turbulence dominated in turbulent transport. The dominated low-$k$ turbulence is different with the EAST long-pulse discharges, since TEM dominated in the low-$k$ turbulence in the EAST RF long-pulse discharges [51, 52], while ITG dominated in the EAST hybrid plasmas.

For the two discharges discussed in section 2.2 (71318 and 78723), temperature predictions were done with the TGLF_VX model. Figure 10(a) shows the comparisons of the electron and ion temperature profiles obtained from the predictions with those from the measurements for discharge 71318 at $t = 4.5$ s (sawtooth). The result shows that the gross agreement of the temperature profiles is reasonable. The predicted temperature profiles of 78723 at $t = 4.1$ s from TGYRO are shown in figure 10(b) (fishbone). The predicted ion temperature profile has good agreement with the experimental fit profile, which is similar to the 71318’s result. The predicted electron temperature profile of 78723 is much lower than the experimental one in the fishbone region ($\rho < 0.3$, $\Delta T_e(0) \sim 0.7$). Neoclassical and turbulent transport in the core region are calculated in TGYRO (figure 11) for discharge 78723 at $t = 4.1$ s. The ion energy flux (figure 11(b)) calculated from TGLF and NEO is appropriate, since the predicted ion temperature profile is reasonable. The neoclassical energy flux (figure 11(b), green) is comparable with the turbulent energy flux (figure 11(b), red) even larger in the ITB region for ions. The decrease of the turbulence, which drops to neoclassical level, should lead to the increase of the ion temperature. The $k$ spectrum of the linear growth rate and frequency of the most unstable modes for 78723 at $t = 4.1$ s is shown in figure 12 for the ITB foot ($\rho \sim 0.3$) and ITB region ($\rho \sim 0.2$). Linear analysis shows that the high-$k$ ($k_y > 1$) mode instability is stronger in the ITB foot ($\rho = 0.3$), mostly the ETG modes.
(figure 12(a)). In the ITB region, high-k mode instability (ETG) is suppressed and it is found that ITG modes dominate in the low-k ($k_y < 1$) region, which is mainly responsible for driving the ion turbulent energy flux. The suppression of high-k modes (ETG) in the ITB region decreases the interaction between low-k and high-k turbulence, which would enhance both ion and electron energy fluxes [60]. It is well known that $E \times B$ flow shear [61, 62] has a stabilizing effect on the low-k micro-instabilities, such as the ITG and TEM modes. To study the effect of $E \times B$ flow shear on the ion energy transport in the EAST hybrid discharge, the predictions of the ion energy transport by TGYRO with the $E \times B$ on or off artificially are performed and the results are similar. The ion energy transport is insensitive to the $E \times B$ flow shear in the EAST hybrid discharge.

Since the predicted electron temperature profile of 78723 at $t = 4.1$ s is much lower than the experimental one in the fishbone region ($\rho < 0.3$), the electron energy flux in the fishbone region should be smaller in fact than that calculated from TGYRO (figure 11(a)), which corresponds to the predicted electron temperature (figure 10(b), dash line, red). The electron energy flux is dominated by the turbulent flux (figure 11(a)) and the reduction of electron energy flux in experiments should be from the suppression of turbulence. Since no MHD activities are considered in the TGYRO prediction, the fishbone may play an important part in the difference between the predicted and experimental profile for electron. The result from ASDEX-U [63] shows that the fishbone activities result in a radial electric field and HL-2A’s result [64] shows that the fishbone activities induce a poloidal flow, which would suppress the turbulence. The mechanism of turbulence suppression from fishbone instabilities in the EAST hybrid plasmas is not clear and needs more investigation.

4. Power threshold of ITB formation in the EAST hybrid plasmas

As discussed in section 2, the flat central $q$ profile with fishbone instabilities would be the best one to reach higher performance and long-pulse operation in the EAST H-mode scenario with the ITB in all channels. A parametric dependence of the power threshold in the database was examined, showing the formation conditions in EAST hybrid H-mode discharges. An attempt of ITB power threshold identification for weak or reversed-shear plasmas by the ITB Database Group and the ITPA Topical Group on Transport and Internal Barrier Physics resulted in a scaling law of ion ITB formation power threshold, as below [10]:

$$P_{\text{Th}}^{\text{ITB}} = 3.14 n_{\text{e}}^{0.9} d_{\text{H1}}^{-2.13} k_{\text{95}}^{1.34} (0.2 + \delta_{\text{95}})^{-0.15} B_{\text{i}}^{0.23}. \tag{1}$$

In this expression, $k_{\text{95}}$ and $\delta_{\text{95}}$ are, respectively, the elongation and triangularity of the plasma cross-section at 95% of the volume averaged flux surface, and the units are $10^{19}$ m$^{-3}$ for $n$ and T for $B_i$. Although the scatter is large, the expression certainly describes the trend of a rather strong $n$ dependence, which is nearly linear. Figure 13 shows the scaling of the power threshold for the formation of the ITB in the EAST hybrid plasmas and the database is from [29]. It is found that the power threshold in the EAST hybrid plasmas is consistent with the scaling law for other tokamaks, as described in [10]. And the power of $P_{\text{Loss}}$ [\(P_{\text{Loss}} = P_{\text{abs}} + P_{\text{OH}} = dW/dt\), where $P_{\text{abs}}$ is the absorbed heating power, $P_{\text{OH}}$ is the ohmic heating power and $dW/dt$ is the change rate of stored energy to achieve ITB formation condition is $\geq 3.5$ MW in the EAST hybrid H-mode operation.

Before the formation of the ITB, there are two types of MHD activities appearing in the EAST hybrid plasmas. One is the target plasma with sawtooth oscillation, another is without sawtooth oscillation. Figure 14 shows typical discharge 56933 with the ITB and the target plasma with sawtooth before ITB formation, which is observed from the SXR signals (figure 14(e), gray area). EAST discharge 56932 shows another situation of the target plasma without sawtooth oscillation before ITB formation (figure 15). This observation shows
Table 2. Comparison of parameters for EAST hybrid and steady-state discharges.

| Shot   | 73999 | 81163 | 78977 |
|--------|-------|-------|-------|
| $I_p$ (MA) | 0.4   | 0.4   | 0.45  |
| RF + NBI (MW) | 3.1   | 4     | 4     |
| $\beta_N$ | 0.9   | 1.5   | 1.9   |
| $\eta_95$ | 6.6   | 6.8   | 3.7   |
| $H_{89}$ | 1.4   | 1.9   | 2.2   |
| Scenario | Steady-state | Steady-state | Hybrid |

Figure 14. Typical ELMy H-mode discharge 56933 with sawtooth before ITB formation: (a) plasma current ($I_p$); (b) stored energy; (c) normalized beta ($\beta_N$); (d) NBI and LHW power; (e) core and edge SXR signals.

Figure 15. Typical ELMy H-mode discharge 56932 without sawtooth before ITB formation: (a) plasma current ($I_p$); (b) stored energy; (c) normalized beta ($\beta_N$); (d) NBI and LHW power; (e) core and edge SXR signals.

the importance of the $q$ profile in the triggering of ITB. In fact, for discharge 56932, a sustained fishbone instability is observed before the ITB triggering (figure 15(e), gray area), while in discharge 56933 fishbone is accompanied with ITB formation. This indicates that power threshold is a necessary condition for ITB formation, since it is found that the ITB of electron density and electron temperature are related to the fishbone instabilities in sections 2 and 3. The central flat $q$ profiles clamped by the fishbone or other low $n$ MHD modes are currently considered as a necessary condition of the ITB formation in these experiments. The ITB can be triggered either with a pre-developed (#56932) central flat $q$ profile, or together with the formation of the central flat $q$ profile (#56933). The LHW power is supplied by a 2.45 GHz LHW system and 4.6 GHz LHW system in the sawtooth-free discharge (#56932), while in the sawtooth discharge (#56933) only a 4.6 GHz LHW power is applied. The contribution of the 2.45 GHz LHW is to modify the $q$ profile by depositing at the plasma edge in the current ramp-up phase. This will change the condition when the fishbone mode appears. However, due to the relatively weaker heating effect of LHW than NBI, the power of 2.45 GHz LHW does not contribute to the ITB power threshold.

5. Discussion and summary

In summary, extensive experiments of hybrid scenario development have been carried out on EAST tokamak recently with the ITER-like tungsten divertor. The maximum $\beta_N$ increases from 1.9 (EAST#71320, $\beta_N \sim 1.9, I_p \sim 0.4$ MA, $\eta_95 \sim 4.7, B_T \sim 1.6$ T, 4.8 MW NBI and 1 MW 4.6 GHz LHW) to 2.1 (EAST#78987, $\beta_N \sim 2.1, I_p \sim 0.45$ MA, $\eta_95 \sim 3.7, B_T \sim 1.5$ T, 3 MW NBI and 1 MW 4.6 GHz LHW). The $G$ value is promoted from 0.13 (EAST#71320, $\beta_N \sim 1.9, H_{89} \sim 1.5, \eta_95 \sim 4.7$) to 0.3 (EAST#78977, $\beta_N \sim 1.9, H_{89} \sim 2.2, \eta_95 \sim 3.7$). The high-performance phase ($\beta_N \geq 1.8$) is sustained for 2 s and the preset duration of the flat-top phase is limited by the engineering issue of the NBI heating system, and not limited by the plasma instability or physical issue. A flat central $q$ profile with fishbone instabilities would be the best choice to explore the higher performance and long-pulse operation in the EAST hybrid H-mode scenario.
with the ITB in all channels. The formation of ITB for the electron density is related to fishbone activities. The modeling result shows that the fishbone instabilities have a suppression on electron turbulent transport, while the ITB of ion temperature is due to the suppression of high-k modes (ETG). The mechanism of turbulence suppression from fishbone instabilities in the EAST hybrid plasmas is not clear and needs more investigation. It is found that the power threshold for ITB formation in the EAST hybrid plasmas is consistent with the scaling law for other tokamaks, as described in [10]. And the power threshold for ITB formation is \( \geq 3.5 \) MW in the EAST H-mode operation.

In contrast, the \( G \) values for the steady-state operation with RF heating only and the hybrid operation with the ITB on EAST tokamak have been compared, as shown in figure 16. For the EAST steady-state RF-only discharge \#73999 (\( \beta_N \approx 0.9, \beta = 1.4, q_95 \approx 6.6, 100 \) s long-pulse H-mode) [28], \( G \approx 0.03 \). And another steady-state discharge \#81163 (\( \beta_N \approx 1.5, \beta = 1.9, q_95 \approx 6.8, 24 \) s long-pulse H-mode) [28], \( G \approx 0.06 \), twice that of \#73999’s. This is reasonable, since \#81163 has higher performance in the steady-state operation. For hybrid discharge with ITBs \#78977 (\( \beta_N \approx 1.9, \beta = 2.2, q_95 \approx 3.7 \)), \( G \approx 0.3 \), about five times that of \#81163’s. The parameters for these three discharges are listed in table 2. In these two scenarios developed on EAST, it is important to expand the operational regime in the hybrid operation [29–31] and steady-state operation [28]. Further investigation of extending these operational regimes, such as expanding the ITB foot outwards, would be important for the development of the hybrid and steady-state scenarios for ITER and CFETR.

**Figure 16**. Comparison of the normalized fusion performance parameter \( G = H_{\beta N}/q_{95}^2 \) for EAST steady-state RF-only discharge 73999 (\( \beta_N \approx 0.9, H_{\beta} = 1.4, q_{95} \approx 6.6 \)) and 81163 (\( \beta_N \approx 1.5, H_{\beta} = 1.9, q_{95} \approx 6.8 \)) and the hybrid discharge 78977 (\( \beta_N \approx 1.9, H_{\beta} = 2.2, q_{95} \approx 3.7 \)).

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