Long Pulse H-Mode Scenarios Sustained by RF Heating on EAST*

GAO Xiang (高翔), LI Guoqiang (李国强), ZHANG Tao (张涛),
YANG Yao (杨曜), GONG Xianzu (龚先祖), LIU Zixi (刘子西),
REN Qilong (任启龙), LIU Haiqing (刘海庆), ZENG Long (曾龙),
YU Yaowei (余耀伟), LIU Shaocheng (刘少承), LIU Xiaojun (刘晓菊),
ZHANG Shoubiao (张寿彪), CAI Huishan (蔡辉山), WU Xuemei (吴雪梅),
LI Jiangang (李建刚), and the EAST team

1Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
2Department of Modern Physics, School of Physical Sciences,
University of Science and Technology of China, Hefei 230026, China
3Department of Physics, Soochow University, Soochow 215006, China

Abstract EAST has demonstrated its capability of long pulse operation using RF heating (LHCD and ICRF) in past experiments. One key issue to realize the long pulse H-mode experiments is to sustain the plasma current for steady state operation. Based on the calculations of the transport code ONETWO and its coupled RF code GENRAY, two scenarios have been proposed to achieve the 10 s H-mode plasma with $I_p=400$ kA, $n_e>4.5\times10^{19}$ m$^{-3}$, $\beta_N=2$, and the 100 s H-mode plasma with $I_p=280$ kA, $n_e>3.5\times10^{19}$ m$^{-3}$, $\beta_N =1.8$ recently. The current drive of lower hybrid wave is an important issue in the two scenarios. An experimental result on lower hybrid current drive in H-mode plasmas on EAST is also presented.

Keywords: long pulse H-mode, RF heating, ONETWO

PACS: 52.55.Fa, 52.55.Rk, 52.55.Wq

DOI: 10.1088/1009-0630/17/6/02

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

1 Introduction

The magnetic fusion concept known as the tokamak has been most successful in producing and maintaining plasma with parameters of density, temperature and energy confinement time closest to those required in a fusion power reactor [1]. An essential feature of tokamak plasmas is the presence of a toroidal current in the plasma itself. Normally, this current is established and maintained in the plasma by a transformer in the centre of the device (inductive drive). This implies that the configuration can be maintained only for a limited time determined by the magnetic flux available. This limitation can be avoided or relaxed if the toroidal plasma current is driven non-inductively. In many experiments, injection of neutral beam (NBI) and powerful radio-frequency (RF) wave in plasma have been utilized to drive this toroidal current. In addition, the tokamak plasma itself produces a non-inductive current, i.e. the bootstrap current due to the pressure gradient.

The ITER baseline scenario [2], i.e. the standard H-mode operation, does not allow a complete non-inductively driven plasma current. The so-called advanced scenarios in fusion experiments seek to improve confinement and stability over the standard H-mode in order to maximize the bootstrap current and thus to lengthen the plasma operation time. Two main types of advanced scenarios, i.e. the steady-state scenario and the hybrid scenario, are being developed in present tokamak devices [3,4]. Typically, the plasma in the steady-state scenario has a central safety factor $q_0 >1.5$, with either weak $|q_0-q_{\text{min}}| \sim 0.5$ or strong $q_0 \gg q_{\text{min}}$ reversed magnetic shear. This kind of $q$-profile is used to obtain internal transport barriers (ITBs), which can provide sufficient bootstrap current for steady-state operation. In the hybrid scenario, the plasma has a stationary current density profile with weak or low magnetic shear, $q_0 \sim 1$ and $q_{\text{min}} \sim 4$. Compared to the ITER baseline scenario, the hybrid scenario allows the plasma to operate at a lower current but higher normalized beta, $\beta_N$, and could substantially lengthen the discharge duration. In order to lengthen the pulse length of the H-mode plasma, advanced scenarios are being developed in present tokamak devices, such as JET [5−9], JT-60U [10−12], DIII-D [13], ASDEX-Upgrade [14,15].

In the 2012 campaign, a 32 s (about $20\tau_R$, where $\tau_R$ is current diffusion time) H-mode with small ELMs has been achieved on EAST [16]. The first wall is molybdenum and the divertor is covered by carbon

*supported by the National Magnetic Confinement Fusion Program of China (Nos. 2014GB106000, 2014GB106001, and 2014GB106003) and National Natural Science Foundation of China (Nos. 11275234, 11321092, 11305215, 11305208, 11405214) and CAS Hefei Center for Scientific Research Program of China (No. 2015SRG-HSC010)
tiles. A 1.8 MW lower hybrid wave (LHW) and a 0.7 MW wave in ion cyclotron range of frequency (ICRF) are combined to heat the target plasma with $B_l = 1.9$ T, $I_p = 0.28$ MA, $\varphi_{95} \sim 6.8$, $<n_e> = 2 \times 10^{19}$ m$^{-3}$ ($n/n_G \sim 0.5$, where $n_G$ is the Greenwald density limit), $\delta = 0.5$ and $\kappa = 1.7$. Due to the low heating power, the $\beta_N$ is less than 1, which is far away from the MHD limit (4-5, estimated using $4 \times \tau_i$). The surface loop voltage ($V_{loop}$) is approximately in the range of 0.15-0.25 V. The ELM frequency is very high (0.5-1 kHz) and the energy loss rates of these small ELMs are typically < 1%, much less than that for the type-I ELM observed on EAST (5% - 8%). This result demonstrated the capability of EAST on long pulse H-mode operation with RF heating. Based on the H-mode operation and recent upgrade of the heating power on EAST, two experiments will be planned in the next step. The first experiment is to realize a stationary 10 s type-I ELMy H-mode with $I_p = 400$ kA, $B_l = 1.8-2.5$ T, $H_{98} \sim 1$, $\beta_N \sim 2$. The second experiment aims at 100 s type-I ELMy H-mode at relatively lower plasma parameters ($I_p = 280$ kA, $B_l = 1.9$ T, $H_{98} \sim 1$, $\beta_N < 2$). One key issue to achieve long pulse operation is to maintain the plasma current. Predictions of the two planned experiments have been done using transport code ONETWO [17] and its coupled RF code GENRAY [18]. Based on these calculations, two scenarios for the two planned experiments have been proposed in section 2. Due to the importance of current drive by LHW in the two experiments, a preliminary study of lower hybrid current drive in H-mode plasma will be presented in section 3. Lastly, a discussion and summary will be given in section 4.

### 2 Current calculations for long pulse H-mode plasmas using RF heating

In the previous experiments, heating power on EAST is relatively low and the $\beta_N$ is generally less than 1. In the next campaign, a new LHCD system at frequency of 4.6 GHz with a total power of 4 MW will be installed and the ICRF power will be upgraded to 12 MW with the new antennae [19]. By virtue of the upgrade of the EAST RF heating power system, higher $\beta_N$ is possible. Based on the energy confinement time scaling law (ITER98y2), we have estimated the required power for EAST plasma to achieve higher $\beta_N$ in the case of $H_{98} = 1$ (Fig. 1). The required power is not sensitive to the plasma current (since in the ITER98y2 scaling law, $\tau_E$ is proportional to $I_p^{93}$), but very sensitive to the $\beta_N$ and the density. For $\beta_N < 2$, $n_e = 4 \times 10^{19}$ m$^{-3}$, the required power is about 7 MW which is expected in the coming EAST campaign.

![Fig.1](image_url) The required heating power vs $\beta_N$ for different line average densities in the case of $H_{98} = 1$. The solid lines are for $I_p = 300$ kA; the dashed lines are for $I_p = 400$ kA

One of the key issues for long-pulse discharge is to sustain the plasma current. The plasma current is the combination of Ohmic current, auxiliary driven current (from NBI or RF waves) and bootstrap current. Previously the plasma performance of EAST is low (low density and low beta), so the fraction of bootstrap current is small. But the efficiency of LHCD is relatively high at low density. For EAST 32 s H-mode discharge [16], the plasma current is mainly driven by LHCD, with some small Ohmic current; while for 400 s L-mode discharge [20], the plasma current is almost entirely from LHCD. For the two planned experiments, i.e. the 10 s H-mode with $I_p = 400$ kA, $H_{98} \sim 1$, $\beta_N \sim 2$ and the 100 s H-mode at relatively lower plasma parameters ($I_p = 280$ kA, $H_{98} \sim 1$, $\beta_N < 2$), we have done some numerical simulations to calculate how to sustain the current and to see whether the magnetic flux is enough for the current sustainment with the available RF heating power. The simulation is performed with transport code ONETWO and its coupled RF code GENRAY. In the simulations, the density and temperature profiles are fixed. GENRAY was used to calculate the driven current and ONETWO was used to capture the evolution of the plasma current to steady-state. Then each component of current profiles could be calculated. We have done such calculations for EAST discharge 40823. The calculated surface voltage is about 0.31 V which is close to the experimental value of 0.3 V. For the prediction of the two planned experiments, we proposed two scenarios for EAST long-pulse H-mode discharges. The parameters of the two scenarios are shown in Table 1. The major difference between the two scenarios are the plasma current $I_p$ and the $\beta_N/\beta_B$ values. In the two scenarios, the density and temperature profiles are based on EAST experimental results, but scaled to match the desired line-average density and $\beta_N$. Scenario 1 is based on the EAST discharge 38300 while scenario 2 is based on EAST discharge 40823.

**Table 1.** Parameters of the two proposed scenarios for EAST long-pulse H-mode. $n_e$ is the line averaged density and $f_{GW}$ is the density normalized to Greenwald density.

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_l$ (T)</td>
<td>1.9</td>
</tr>
<tr>
<td>$I_p$ (kA)</td>
<td>400</td>
</tr>
<tr>
<td>$n_e$ (10$^{19}$ m$^{-3}$)</td>
<td>4.5/0.78</td>
</tr>
<tr>
<td>$\beta_N/\beta_B$</td>
<td>2.0/1.8</td>
</tr>
<tr>
<td>$P_{LHW}$ (MW)</td>
<td>1.5</td>
</tr>
<tr>
<td>$P_{ICRF}$ (MW)</td>
<td>5</td>
</tr>
<tr>
<td>Pulse length (s)</td>
<td>10</td>
</tr>
</tbody>
</table>

449
The plasma in discharge 38300 (shown in Fig. 2) with $B_t = 1.9 \, \text{T}$, $I_p = 400 \, \text{kA}$, $n_e < 4 \times 10^{19} \, \text{m}^{-3}$ was heated by $\sim 1.3 \, \text{MW}$ lower hybrid wave (LHW) and $\sim 0.9 \, \text{MW}$ wave in ion cyclotron range of frequency (ICRF). The electron density and temperature were measured by Thomson scattering diagnostics [21] and the $T_i$ profile was taken from X-ray imaging crystal spectrometer (XCS) [22]. The $T_e$ profile is fitted with a tension spline function [23]. The XCS measurement on EAST has merely the central region data, so $T_i$ is scaled from $T_e$ at the edge region to match the XCS data at the central region and to get $T_i = T_e$ assumption is reasonable.

In these fittings, the knot locations are chosen to make the fitted profile monotonic and smooth. The fitted density profile is also checked with the line average density measurement. Fig. 3 shows the $T_e$, $T_i$ and $n_e$ profiles at $t=3.9 \, \text{s}$.

In scenario 1, the density and temperature profiles in Fig. 3 were scaled to make line average density $< n_e > = 4.5 \times 10^{19} \, \text{m}^{-3}$, and $\beta_N = 2$. The density and temperature profiles after scaling are shown in Fig. 4(a) and (b), respectively. These profiles will be used for the current calculations in scenario 1. With the transport code ONETWO and its coupled RF code GENRAY, we evolve the current to steady state and calculate each current component in the steady-state. The bootstrap current is calculated from the Sauter model [24,25]. The parameters of LHCD are: absorbed power $P_{\text{LHCD}} = 1.5 \, \text{MW}$, parallel refractive index $n_{\text{p}} = 2.1$, wave frequency $f = 2.45 \, \text{GHz}$. Fig. 4(c) gives the final $q$ profile and Fig. 4(d) gives the profiles of each current component. It is a normal reversed $q$ profile, but $q_{\text{min}} \approx 0.2$ is small, since LHCD power deposits at this location. The bootstrap current $I_{\text{bs}} \approx 174 \, \text{kA}$ and LHCD driven current $I_{\text{LHCD}} \approx 114 \, \text{kA}$ lead to an Ohmic current $I_{\text{ohm}} \approx 112 \, \text{kA}$ and loop voltage at plasma surface $V_{\text{surf}} \approx 0.08 \, \text{V}$. On EAST, the voltage-second for flattop is about 4 Vs, so for this scenario $V_{\text{surf}} = 0.08 \, \text{V}$ will make the voltage-second high enough to sustain 10 s.

In scenario 2, the density and temperature profiles in EAST discharge 40823 (shown in Fig. 5) were scaled to make $< n_e > = 3.5 \times 10^{19} \, \text{m}^{-3}$, $\beta_N = 1.8$. The ONETWO and GENRAY codes are used to evolve the current to steady state. In the steady state, the bootstrap current $I_{\text{bs}} \approx 173 \, \text{kA}$, LHCD driven current $I_{\text{LHCD}} \approx 93 \, \text{kA}$, Ohmic current $I_{\text{ohm}} \approx 14 \, \text{kA}$, toroidal voltage at plasma surface $V_{\text{surf}} \approx 0.02 \, \text{V}$. So EAST has enough flux to sustain 100 s discharge in scenario 2. The density, temperature, $q$ and current profiles in steady state are shown
in Fig. 6. It has a strong reversed $q$ profile, and the $q_{\text{min}}$ is 2.6. So there will be no dangerous instability of 2/1 or 3/2 NTMs.

![Graphs showing EAST discharge parameters](image1)

**Fig.5** Upper figure: parameters of EAST discharge 40823 with $I_p > 280$ kA, $B_t = 1.9$ T. Lower figures: density and temperature profiles measured by Thomson scattering

![Graphs showing scenario profiles](image2)

**Fig.6** Profiles of scenario 2. (a) Preset electron density profile, (b) Preset electron and ion temperature profiles, (c) Calculated $q$ profile at steady state, (d) Calculated profiles of total current and each current component

### 3 Study of lower hybrid current drive in H-mode plasmas

A power of 4 MW at 2.45 GHz LHW system has been installed in EAST. It contains 20 main waveguides with a $5 \times 4$ alignment. The parallel refractive index of LHW could be varied from 1.85 to 2.6 by phase adjustment. The LHCD efficiency (typically in L mode plasma) has been investigated in ASIPP with quite a few studies \[26,27\] and references there in. The experimental LHCD efficiency, $\eta_{\text{exp}}$, is defined as $n_e I_{\text{LH}} R / P_{\text{LH}}$, where $n_e$ is the plasma density, $I_{\text{LH}}$ is the driven current by the lower hybrid wave injection, $R$ is the major radius of EAST, $P_{\text{LH}}$ is the LHW power. In previous studies, it has been pointed out that the LHCD coupling and current drive efficiency in high density regime are two critical issues for the LHCD in H-mode plasma.

In order to predict the EAST long pulse operation, the EAST lower hybrid current drive in the H-mode discharge has been investigated, using the data from the 2012 EAST campaign. This was done by studying the LHCD modulation discharges. One typical LHW modulation discharge is presented in Fig. 7. The main parameters in this discharge (EAST discharge 41989) are: $I_p \sim 450$ kA, $P_{\text{ICRF}} \sim 1.2$ MW, modulating LHW power $P_{\text{LH}} \sim 1.2$ MW (seen in Fig. 7(a)). The H-mode is triggered after the ICRF injection. In the H-mode with LHW modulation phase, the loop voltage is modulated with the LHW period. The modulated LHW power was expected to mitigate the ELMs by the helical current filaments in the SOL region \[28\]. In a time window ($t = 5.1-5.4$ s) where density (line integrated) and plasma current are nearly constant, it is shown in Fig. 7(b) that the loop voltage is lower with the LHW power, while the loop voltage is higher without the LHW power. By averaging the data in several LHW modulation periods, the normalized loop voltage change, $\Delta V / V$, is $\sim 0.178$ in this discharge.

![Graphs showing loop voltage change](image3)

**Fig.7** Loop voltage changed by LHCD on H-mode plasma. (a) Overview of an LHW modulation discharge, (b) Loop voltage change with the LHW modulation
To evaluate the LHCD contribution in the long pulse discharge, Fig. 8 shows an analysis on the change of the loop voltage by LHCD of 1.2 MW. Here, the plasma density is $(2.8-4.5) \times 10^{19} \text{ m}^{-3}$. The plasma current varies from 300 kA to 450 kA. In fact, the normalized loop voltage change is a rough description of how much magnetic flux was saved by LHCD. It is shown that the flux saved, or, the ability of driving current is decreasing with the plasma density in these H-mode plasmas. This is similar to the study of Ref. [27]. Here we investigated the loop voltage change during the LHCD H-mode plasmas, rather than the LHCD efficiency $\eta_{\text{exp}}$. This indicates that all other effects such as hot conductivity and bootstrap current have been considered as part of the whole LHCD effect. This could be correct from the engineering point of view (flux saving).

Fig. 8 The LHCD with different density on H-mode discharges, where the plasma density is $(2.8-4.5) \times 10^{19} \text{ m}^{-3}$, and the plasma current varies from 300 kA to 450 kA.

4 Discussion and summary

We have done current calculations using ONETWO and GENRAY code. The present analysis is based on the profile shapes measured in experiment. However, the $T_i$ profile in the edge is in fact assumed. The current driven efficiency model we are using in GENRAY is described in Ref. [31]. The current driven efficiency $\eta$ a function of $\eta = (Z, \varepsilon, \theta, w)$, where $Z$ is the ion charge number, $\varepsilon$ the inverse aspect ratio, $\theta$ is the poloidal location and $w = \omega/k_{||}v_e$ is the RF wave phase velocity normalized to the electron thermal velocity. So the ion temperature will NOT affect the $\eta$. That is, the assumption of the $T_i$ profile in the present work would not affect the results. However, the effective charge number $Z_{\text{eff}}$ does have an effect on the $\eta$. We have done the simulation by increasing the $Z_{\text{eff}}$ 50% and found that the driven current reduces less than 15%. This indicates the effect of $Z_{\text{eff}}$ is small.

The results shown in section 2 indicate that the volt-second can sustain the plasma currents in the two scenarios. However, another two important issues i.e. MHD stability and heat flux in the divertor target, have not been considered yet. Both issues could limit the plasma performance and plasma discharge duration. In scenario 1, although the plasma with $q_{\text{min}} \geq 1$ will be free of sawtooth which is one important trigger factor of the neoclassical tearing modes (NTMs), the occurrence of dangerous $2/1$ and $3/2$ NTMs is still possible, which will degrade the plasma beta and even terminate the discharge. It is noted that the NTMs have been observed on EAST [29,30]. The real-time stabilization of the NTMs using ECCD will be available in the near future on EAST. As shown in section 2, the $2/1$ and $3/2$ NTMs could be avoided in scenario 2 due to $q_{\text{min}} > 2$. In both scenarios, if the assumed 20% of the injected power radiated in the plasma core, then 80% of the power will cross the separatrix and transport to the divertor target. According to the scaling of divertor power footprint width on EAST, the heat load on divertor target is estimated to be 6.6 MW/m² and 4.6 MW/m² for scenario 1 and scenario 2, respectively.

To facilitate the high power operation, the upper divertor on EAST has been upgraded to ITER-like tungsten monoblock target structure with active water cooling, to allow for high heat load on divertor targets up to 10 MW/m². In the near future, the bottom divertor will also be upgraded to this kind of W target. It seems that the heat load in both scenarios will not be a big problem.

In summary, we have proposed two scenarios to realize RF heating sustained long pulse H-mode operation with $\beta_N \leq 2$ based on the current calculations using ONETWO and GENRAY codes. Results show that the volt-second available on EAST can sustain the two operation scenarios. Based on this volt-second analysis, it is expected that the realization of the two planned experiments, i.e., a stationary 10 s type-I ELMy H-mode with $I_p = 400$ kA, $H_{98} \sim 1$, $\beta_N \sim 2$ and an 100 s type-I ELMy H-mode at relatively lower plasma parameters ($I_p = 280$ kA, $H_{98} \sim 1$, $\beta_N < 2$), will be possible.

References

GAO Xiang et al.: Long Pulse H-Mode Scenarios Sustained by RF Heating on EAST


23 Cline A K. 1974, Commun. ACM, 17: 218


(Manuscript received 3 August 2014)
(Manuscript accepted 12 January 2015)
E-mail address of GAO Xiang: xgao@ipp.ac.cn

453