Integrated plasma scenario analysis for the HL-2M tokamak

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Abstract
HL-2M is a new medium-sized tokamak under construction at the Southwestern Institute of Physics, dedicated to supporting the critical physics and engineering issues of ITER and CFETR. Analyzing integrated plasma scenarios is essential for assessing performance metrics and foreseeing physics as well as the envisaged experiments of HL-2M. This paper comprehensively presents the kind of expected discharge regimes (conventional inductive (baseline), hybrid and steady-state) of HL-2M based on the integrated suite of codes METIS. The simulation results show that the central electron temperature of the baseline regime can achieve more than 10 keV by injecting 27 MW of heating power with a plasma current of $I_p = 3$ MA and Greenwald fraction $f_G = 0.65$, with the thermal energy and $\beta_N$ reaching 5 MJ and 2.5, respectively. The hybrid regime with $f_{ni} = 80\%$–$90\%$ can be realized at $I_p = 1$–$1.4$ MA with $f_G$ around 0.5, where $\beta_N$ is 2.3–2.5 with $H_{98}(y,2) = 1.1$. Because of the effect of the on-axis NBCD, the hybrid steady state, at $I_p = 1.0$ and 1.2, can be achieved more easily than the steady state regimes with reversed shear, corresponding to $\beta_N = 2.6$ and 3.4. Such studies show that HL-2M is a flexible tokamak with a significant capacity for generating a broad variety of plasmas as a consequence of the different heating and current drive systems installed.

Keywords: HL-2M tokamak, integrated modeling, operation scenarios

(Some figures may appear in colour only in the online journal)
to studying high-performance plasma physics issues, the plasma edge and divertor physics by exploring various divertor concepts (e.g. snowflake, tripod) [7–9], as well as plasma–wall interaction. The high power heating and current drive system allows the machine to study a variety of operation scenarios. Analyzing these integrated scenarios for HL-2M plasmas has important significance for assessing the performance metrics, foreseeing the physics experiments and guiding the engineering design of the machine, as well as further improving the database and providing references for fusion reactors.

Current operation scenarios [2, 10–15] are mainly classified in three types: the conventional ELMy H-mode discharge (the so-called baseline or reference scenario), the hybrid and the steady state. The baseline normally has a high fusion gain $Q$ ($Q = 10$ for ITER), with a high plasma current and safety factor at 95% flux surface ($q_{95}$) around 3. The hybrid scenario is dedicated to providing high neutron fluence, with a lower plasma current compared to the conventional operation regime.

The hybrid operation regime normally possesses high beta and good confinement as well as longer pulse duration and lower plasma current compared to the conventional operation regime. It may be a reliable transitional scenario from conventional inductive operation to full non-inductive operation for ITER [2]. At least from the MHD stability point of view a low magnetic shear with a central safety factor of $q_0 \sim 1$, is beneficial [16–18]. The fraction of noninductively driven current is normally around 80% with a 40%–45% bootstrap current fraction.

The steady state scenario aims to realize full noninductive operation (with a >45% bootstrap current fraction). Considering the required enhancement of the stability and the confinement for generating enough bootstrap current, two scenarios are possible: weak reversed shear with the internal transport barrier (ITB) and $q_0 \sim 2.5$, $q_{\text{min}} > 2.0$, $q_0 - q_{\text{min}} \sim 0.5$ as well as the steady-state hybrid scenario with $q_0 \sim 1$, $q_{\text{min}} \sim 1$, where the normalized radius of $q_{\text{min}} (\rho_{\text{min}})$ is normally between 0.2–0.5.

In order to provide analysis, predict the full time evolution of a tokamak discharge and further optimize the operation scenarios, integrated modeling is necessary. In this paper, the possible operation scenarios of the HL-2M tokamak are explored and analyzed by using the 0.5D integrated simulation code METIS [19], and further optimized by the 1.5D full tokamak discharge simulation code CRONOS [20–25].

The paper is organized as follows: section 2 briefly describes the main parameters of HL-2M and its heating and current drive system capability. The METIS code and the assumptions used for the simulation, as well as the benchmark with the HL-2A experiment are presented in section 3. In section 4, the baseline, the hybrid and the full noninductive regimes are analyzed by the METIS code. In section 5, the reference hybrid scenario is further developed by performing more detailed analyses with the CRONOS code. The summary is finally delivered in section 6.

2. HL-2M tokamak

HL-2M is a new medium-sized copper-conductor tokamak under construction at SWIP (as shown in figure 1), dedicated to supporting the critical physics and technique research of ITER and CFETR. It uses demountable toroidal field coils to simplify fabrication and the assembly of the poloidal field coils and the vacuum vessel, meanwhile making further improvements to the machine components possible [6]. Based on this, the flexibility of the experiments is significantly increased. The (up-down) symmetric poloidal coil system, located between the toroidal coils and the vacuum vessel, allows multiple divertor configurations (the standard, the snowflake and the tripod divertor configurations, etc) to be generated with high elongation. The main plasma parameters are greatly increased in contrast to previous tokamaks in SWIP. The first wall, as well as the divertor, is bedded by carbon-fiber-reinforced composite (CFC) in the first phase, and is expected to be fully updated to tungsten in the future.

Three heating and current drive (H/CD) systems, with a total power of 27 MW, will be installed in HL-2M. Fifteen MW of the neutral beam injections (NBI) are provided by three heating windows (two co-current tangent injections (angle: $42^\circ$–$45^\circ$) and one counter-current tangent injection based on four sets of 80kV/45 A bucket deuterium ion sources). The ECRF system on HL-2M is constituted of eight gyrotrons, each of which has a nominal power of 1 MW. Two of those ECRF gyrotrons can be operated with a dual-frequency, i.e. 140 GHz and 105 GHz, and are connected to the upper launcher. The other six gyrotrons can only work at the single frequency of 105 GHz, and are connected to the equatorial launcher. This allows the heating and current drive to be located in a large range of radial coordinates. The toroidal injection angles of the equatorial launcher and upper launcher are respectively in the range of $-20$ to $20^\circ$ and $-25$ to $25^\circ$. Poloidal injection angles of the equatorial launcher and the upper launchers can be respectively varied from $-20$ to $+15^\circ$, $-80$ to $-15^\circ$ (for the poloidal angle, along the horizontal direction of the injection, the degree obtained by the counter-clockwise rotation is minus. For the toroidal angle, the injection degree with the same direction (clockwise) as the magnetic field is minus), shown in figure 2. The lower hybrid current drive (LHCD) has 4 MW at the 3.7 GHz frequency. The LHCD antenna is a full active multi-junction (FAM) with a peak parallel refractive index $n//0$ of 2.25. Such an auxiliary heating system allows...
the machine to heat and control high performance plasmas, as well as a variety of advanced scenarios. The nominal designed HL-2M plasma current \( I_p \) goes up to 3 MA with a 3 T toroidal field. The major radius is 1.78 m with a 0.65 m minor radius. The elongation is higher than 1.8 and the triangularity can be larger than 0.5, as listed in table 1 [6].

3. Simulation assumptions and benchmark with HL-2A experiment

METIS [19, 20] is a fast tokamak discharge simulation code. It has been intensively used for scenario preparation and exploration on a large number of existing or future tokamaks, such as Tore Supra, JET, JT-60SA, ITER and the European DEMO design [26–29]. In order to provide enough flexibility for experiment analysis as well as scenario design, METIS decreases the simulation duration to a minute level based on the use of simplified models mixing a 0D and 1D approach, with some reasonable simplifying assumptions instead of the full complex nonlinear physical model. For instance, the full time-dependent current diffusion equation is solved with analytical expressions of the current sources. The equilibrium evolution is obtained by solving equations for the moments of the Grad–Shafranov equation. The stationary heat and particle transport equations are solved on a radial grid (21 grid points) using simplified source terms; then the various profiles are obtained by using scaling laws for energy and particle confinement. The main assumptions used in the HL-2M simulations are the following:

- The coefficients of heat transport follow the Bohm/gyro-Bohm model [30, 31]. They are adjusted in order to follow the ITER two term scaling law for global confinement (0D) [32].
- The L–H power threshold follows the Y R Martin scaling in 2008 (0D) [33].
- The current drive efficiency of lower hybrid waves is given by scaling based on the LHCD experiments in JET and Tore Supra (0D) [34].
- The location and width of both ECRH and LHCD power depositions are fixed in order to reproduce the time evolution of the plasma self-inductance (0D).
- The density profile prediction for HL-2M is based on three estimates: the density at the separatrix \( n_{\text{sep}} \), the pedestal density and the density peaking factor. \( n_{\text{sep}} \) is calculated using Mahdavi scaling [35]. The pedestal depends on the ratio between the pedestal density \( (n_{\text{ped}}) \) and the separatrix density \( (n_{\text{sep}}) \) consistent with ITPA multi-machine data [36]. The density peaking is predicted by Weißen’s scaling based on JET results, taking into account the collisionality dependence [37] for the baseline with high density and NBI heating. For the reference baseline, hybrid and steady state scenarios this is predicted by the C Angioni formula depending on the Greenwald fraction, the NBI fueling and the major radius \( R_0 \) (0D) [38].
- The bootstrap current and resistance are calculated by the Sauter formula (1D) [39, 40].

Subsequently, these simplified models of heat transport, heating and current drive (NBI, ECRH, LHCD) are benchmarked with HL-2A discharges. The HL-2A 31807 shot, with the H-mode driven by NBI+ECRH+LHCD, is simulated by METIS (the key waveforms such as plasma current \( I_p \), the line averaged density \( n_{\text{avg}} \), and the power of NBI/ECRH/LH are used as the input in METIS) as shown in figure 3. It can be seen that the time evolution of the experimental loop voltage and of the core electron temperature, as well as of the temperature profile obtained by ECE during H-mode are well reproduced by METIS simulations. Note that the drop of the loop voltage is due to both the electron heating (which decreases the plasma resistivity) and the noninductive current driven by LHCD. Here, we consider the increase of \( Z_{\text{eff}} \) that increases the plasma resistivity and decreases the LH current drive efficiency. In the experiments reported \( Z_{\text{eff}} \) increased, due to the increase of impurity, when the additional heating and current drive powers (NBI, LHCD, ECCD) were applied.

4. HL-2M operation scenario analysis based on METIS

In this section, we use METIS to analyze the possible scenarios (such as the baseline, hybrid and steady state) for HL-2M. During the simulation, the engineering limits of the auxiliary heating duration and of the heating loads in the coils are assumed to be free. Thus, operating H-mode plasmas in

![Figure 2. The poloidal injection angle range of the upper and the equatorial ECRF launchers; the resonant layer is shown as a green solid line.](image-url)
these conditions is limited by the available poloidal flux of 14 Wb. Referring to the additional heating implemented on HL-2A, the deposition width of ECRH and LH are respectively assumed to be 0.1 and 0.2 in the normalized radius \( \rho \) for the HL-2M scenario simulation.

### 4.1. H-mode baseline scenarios

The conventional H-mode inductive discharge, called the baseline, normally has a high plasma current and density, aiming for a high fusion gain \( Q \) in ITER, with a low \( q_{95} \) (around 3). The \( q_0 \) is normally the minimum value as the \( q \) profile is monotonic. Usually, significant sawteeth are obtained in these conditions. As a first step in the analysis of the baseline scenario, the density profile assessment based on \( n_e \)-free (where \( n_e \)-free is the number of parameters to define the density profile in METIS, if \( n_e \)-free = 3, the density profile is defined by the center density, edge density and peaking factor. If \( n_e \)-free = 4, the density profile is defined by the center density, edge density, pedestal density and peaking factor) has been carried out with different models and Greenwald fractions.

Two formats of the pedestal density scaling, which couple with the peaking factor to determine the full density profile, are compared. The pedestal depends on the ratio between the pedestal density (\( n_{\text{ped}} \)) and the separatrix density (\( n_{\text{sep}} \)) consistent with the ITPA multi-machine data (\( n_{\text{sep}} \)-free = 3), or which depends on the following formula (\( n_{\text{ped}} \)-free = 4):

\[
n_{\text{ped}} = n_{\text{sep}} \left( \frac{n_{\text{ped}}}{n_{\text{Gr}}} \right)_{\text{ped, exp}}
\]

where \( n_{\text{Gr}} \) is the Greenwald density and the \( n_{\text{ped, exp}} \) is set to be \(-0.1\).

From the ITPA2008 scaling of the L–H transition threshold, the H-mode can be achieved in the nominal condition \( I_p = 3 \text{ MA}, B_t = 3 \text{ T and } f_G = 1 \) (corresponding to the central density \( n_e(0) \approx 2.2 \times 10^{20} \text{ m}^{-3} \) with a power of about 10 MW. Thus, operating H-mode plasmas in these conditions is possible with NBI alone (15 MW). However, operating in such high density regimes will lead to a significant loss of NBI power. Meanwhile, such a high edge density might also be 10%–30% larger than that of the partial detachment, which will cause the confinement to degrade, finally causing H-mode to transit to L-mode. If the edge density is decreased by pumping, stronger fueling is necessary to maintain the global density. In this case, the pedestal density might exceed the pedestal limit, leading to the degradation of confinement. Meanwhile, such high-density coupling with high NBI heating might also cause the impurity to concentrate in the core, leading to the degradation of confinement. Based on the elements considered above, the Greenwald fraction \( f_G \) for the \( I_p = 3 \text{ MA regimes}, \) is selected to be \( f_G = 0.65 \).

For maximum plasma current \( I_p = 3 \text{ MA, } f_G = 0.65 \) and 15 MW NBI heating discharge, when the Angioni peaking factor scaling law is coupled with \( n_e \)-free = 3, the pedestal disappears (black solid line in figure 4(a)). When the Angioni peaking factor scaling law is coupled with \( n_e \)-free = 4, the profile peaks too much (green solid line in figure 4(a)). Thus, it seems that the Angioni density peaking factor scaling law is not applicable for the discharge of high density with high NBI heating, and Weisen’s collisional scaling law appears to be a better choice (red dashed line is coupled \( n_e \)-free = 3 and blue dashed line is coupled \( n_e \)-free = 4). In this case, we choose Weisen’s collisional scaling, coupling \( n_e \)-free = 3, to simulate the baseline of high density with high NBI heating.

In order to decrease the flux consumption during the ramp-up phase, the ramp-up rate of the plasma current is chosen to be 2 MA s\(^{-1}\). The sawtooth effect is not considered during the
simulation. Since the scaling threshold power for transiting from L mode to H mode $PL_{2H} = 7.6$ MW, and considering some possible loss of the input power as it is deposited in the plasma, additional heating power more than 1.5 times $PL_{2H}$ (11.4 MW) is implemented. For the full auxiliary heating scenario (15 MW NBI + 8 MW ECRH + 4 MW LH) as both shown in figure 5 and table 2, the $\beta_p$ can reach 1.0, and the normalized pressure $\beta_N$ can reach 2.5, which is smaller than $4l_i = 3.4$. The increasing internal inductance $l_i$ indicates that the current profile gradually peaks towards the center of the plasma. The bootstrap current fraction $f_{BS}$ and the noninductive current fraction $f_{NI}$ are 0.28 and 0.34, respectively. The central electron temperature $T_e$ is close to the ion temperature $T_i$. When NBI is

**Figure 4.** Electron profile comparison between different scaling laws for $I_p = 3$ MA, $f_G = 0.65$ (a), and $I_p = 2.5$ MA, $f_G = 0.5$ (b). Angioni: for the Angioni peaking factor scaling law, $n_e$-free = 3, the pedestal depends on the ratio between the pedestal density ($n_{eped}$) and the separatrix density ($n_{esep}$) consistent with the ITPA multi-machine data; $n_e$-free = 4: the pedestal density depends on a fixed formula; Weisen: the Weisen collisional scaling law.

**Figure 5.** (a) The waveform of auxiliary heating (PNB:NBI, PEC:ECRH, PLH:LH) implemented during the simulation; (b) the waveform of the plasma current $I_p$, the bootstrap current $I_{BS}$ and the noninductive current $I_{NI}$; (c) time traces of $r_p$, $\beta_p$, $l_i$; (d) the current profile and $q$ profile at 6 s; (e) the electron temperature, ion temperature and density profile at 6 s; (f) the equilibrium flux surface.
implemented solely, $\beta_N$ can reach 1.8 with an $f_{\text{BS}}$ of 0.18. The central electron temperature (5.8 keV) is lower than the ion temperature (6.6 keV), as shown in table 2 (B3).

$I_p = 2 \sim 2.5$ MA are the moderate values of the HL-2M baseline. The low plasma current baseline chosen for the simulation is based on $I_p = 2.5$ MA and $f_{\text{BS}} = 0.5$. Based on the analysis shown in figure 4(b), the Weisen collisional scaling law coupling $n_e/\sqrt{f}$ is used for determining the density profile of the low plasma current baseline. Since a low $q_{95}$ is beneficial for increasing the fusion gain, in order to lower $q_{95}$ down to $q_{95} \sim 3$, the toroidal field $B_t$ is chosen as 2.3 T, as shown in table 3. In order to avoid the possible current hole during the ramp-up phase, the plasma current ramp-up rate is chosen as 1 MA s$^{-1}$ for the reference baseline. Since the absorption efficiency of LH is very low at high density, especially in the center of the plasma, the reference baseline is mainly performed by the NBI and ECRH.

When full auxiliary heating is implemented (table 3 RB1), $T_e$ and $T_i$ can reach 9.3 keV and 10 keV, respectively. The normalized pressure $\beta_N$ can reach 2.7, and $f_{\text{BS}}$ and $f_{\text{BS}}$ are 0.26/0.32, respectively. The thermal stored energy was able to reach 3.2 MJ. If the auxiliary heating is only implemented by NBI (table 3 RB2), the $T_e$ decreases obviously to 6.7 keV, and the $T_i$ is still around 9.8 keV.

The normalized pressure $\beta_f$ further decreases to 2.1, and $f_{\text{BS}}$ and $f_{\text{BS}}$ are 0.20/0.25 with only NBI. The thermal stored energy further decreases to 2.6 MJ. Considering the critical power for the transition from L-mode to H-mode is 4.43 MW, the conventional H-mode with a type I ELM regime can also be driven by only 8 MW ECRH (table 3 RB3). In this case, the $T_{\text{ecrh}}$ is 7.7 keV and $T_{\text{ecrh}}$ decreases to 4.2 keV, the normalized pressure $\beta_N$ is 1.5, the $f_{\text{BS}}$ is 0.13 and the thermal stored energy is 2.0 MJ.

These simulations show that a broad range of baseline scenarios can be obtained in HL-2M with a very significant flat-top phase duration. This flexibility allows for detailed physics analyses both in the core and edge plasma regions. For instance, changing the ratio $T_{\text{ecrh}}/T_i > 1$ to $T_{\text{ecrh}}/T_i < 1$ can help in the investigation of different turbulence regimes or power exhaust mechanisms.

### 4.2. Stabilization of $q$ profile

Controlling the $q$ profile is essential in the hybrid scenario in order, at least, to control the onset of MHD modes at high $\beta_N$ which is characteristic of such scenario. However, sometimes reversed or even flat core $q$ profiles are not stationary, and, as with the baseline scenarios studied in section 4.1, when the toroidal current diffuses the $q$ profile becomes fully monotonic. Therefore, analyzing the actuators to stabilize the $q$ profile is a key point which should be considered first.

To further clarify the role of the current profile, the regime is shown in table 3 RB1. The ramp-up rate of the plasma current is 1 MA s$^{-1}$, and full auxiliary heating is implemented at 2.5 s. It is observed that a fluctuation is generated during the evolution of $q_0$, as shown in figure 6(a). The 1 MA s$^{-1}$ ramp-up rate does not make the plasma current profile off-axis at 2.5 s (figure 6(g)). As the auxiliary heating is implemented, a valley (called an inductive valley in the following) in the inductive current profile is generated at the peak location of the auxiliary current drive, shown by the black rectangles in figure 6(f); then the plasma transits from L-mode to H-mode. The inward diffusion of the inductive valley tends to lead to the decrease of $q_0$. This offsets the effect of the increasing auxiliary current drive, keeping $q_0$ unchanged during 2.5 s–3.7 s.
Subsequently, a gradual increase of the plasma temperature prompted by the additional heating causes a larger off-axis noninductive current drive (figures 6(d) and (e)). Meanwhile, the inductive valley does not move inwards obviously (figure 6(f)). This leads to the increase of $q_0$ during 3.7 s–4.5 s (figure 6(a)). After that, the inward diffusion of the inductive valley dominates again, causing $q_0$ to decrease for 4.5 s–6.2 s (figures 6(a) and (f)). Therefore, we guess there are two ways to stabilize $q_0$: (i) increasing the noninductive current fraction $f_{ni}$ to weaken the effect of inductive valley diffusion; (ii) decreasing the ramp-up rate of the additional heating power to moderate the major fluctuation of $q_0$. Based on the analysis above, the hybrid scenarios as well as the steady state scenarios are investigated in the following sections, and strategies for the control of the $q$ profile are shown.

### 4.3. Hybrid scenario

Unlike the baseline, the hybrid scenarios normally operate at lower plasma current, i.e. higher $q_{95}$ in order to avoid sawteeth, which could trigger deleterious MHD activity at the high $\beta_N$ values characteristic of this scenario, together with a low core magnetic shear $q$ profile close to 1. Such a scenario is explored in this section with the aim of finding optimized $q$ profile control at a high noninductive current fraction. For this purpose, the approach found in [22, 24], i.e. concentrating most of the

![Figure 6.](image)

![Figure 7.](image)

### Table 4. The plasma parameters of hybrid scenarios.

| Hybrid | H1 | H2 | H3 |
|--------|----|----|----|
| $I_p$ (MA)/$B_t$ (T) | 1.4/2.2 | 1.0/2.0 | 1.0/2.0 |
| $\kappa/\delta$ | 1.8/0.5 | 1.8/0.5 | 1.8/0.5 |
| $n/R$ (m) | 0.65/1.78 | 0.55/1.78 | 0.55/1.78 |
| $f_G$ | 0.47 | 0.5 | 0.5 |
| $P_{NBI}/P_{ECRH1}/P_{LH}$ ($P_{ECRH2}$) | 10/5/(2) | 6/7/(1) | 6/6/3 |
| $X_{crit}/X_{th}$ ($X_{crit2}$) | 0.34/(0.28) | 0.4/(0.2) | 0.28/0.7 |
| $q_{95}$ | 5.5 | 4.8 | 4.7 |
| $\beta_p$ | 1.3 | 1.7 | 1.6 |
| $\beta_S/\alpha_i$ | 2.3/3.8 | 2.5/3.9 | 2.4/3.4 |
| $f_{AS}/f_{nu}$ | 0.33/0.76 | 0.40/0.86 | 0.41/0.89 |
| $T_{ec}/T_{th}$ (keV) | 8.4/9.2 | 6.7/6.1 | 6.5/5.8 |
| $T_{ped}/T_{ped}$ (keV) | 1.00/0.87 | 1.20/0.86 | 1.30/0.89 |
| $n_{ped}/n_{esep} (1 \times 10^{19})$ | 3.9/1.1 | 2.7/1.1 | 2.5/1.3 |
| $p_{ped}$ (pa) | $1.1 \times 10^6$ | $0.83 \times 10^4$ | $0.86 \times 10^4$ |
| $W_{th}$ (MJ) | 1.3 | 0.85 | 0.82 |
| $H_{th}(\gamma,2)$ | 1.05 | 1.1 | 1.03 |

[Figure 6](image). (a) Evolution of the central safety factor $q_0$; (b) waveform of the plasma current $I_p$; (c) waveform of the auxiliary heating; (d)–(g) current profile comparison of the different time spot (bootstrap current profile $j_p$, auxiliary current drive profile $j_{cd}$, the inductive current profile $j_{in}$, the plasma current profile $j_p$), (h) the density profile from 1.9 s–6.2 s, (i) the electron temperature from 1.9 s–6.2 s.

[Figure 7](image). A comparison between the Angioni and Weison scaling law in $I_p = 1.4$ MA, $f_G = 0.6$, NBI = 15 MW.
off-axis current drive in the plasma region \( \rho = 0.2 \) to \( \rho = 0.4 \), is used. Thus, two ECRH antennas have also been considered in order to have enough flexibility in terms of the ECCD in the plasma region. In addition, the LH is also considered.

In these simulations, the peaking factor for the density profile is determined by Angioni’s scaling law (a comparison between the Angioni and Weison scaling law is shown in figure 7), and the ECCD co-current drive is used. The simulation results show that the hybrid scenario can be achieved at \( I_p = 1.4 \) MA and \( B_t = 2.2 \) T, as shown in table 4 H1. In this case, the minor radius is 0.65 m, and the Greenwald fraction \( f_G \) is 0.47. The 10 MW NBI combined with 5 MW of the first ECCD launcher (deposition location \( X_{ecrh1} = 0.34 \), deposition width is set as \( \rho = 0.1 \)) and 2 MW of the second ECCD launcher (deposition location \( X_{ecrh2} = 0.28 \), the deposition width is set as \( \rho = 0.1 \)) is implemented to drive a flat \( q \) profile around 1 (from \( \rho = 0 \) to \( \rho = 0.4 \)), the bootstrap current fraction \( \beta_f \) can reach 2.3, the bootstrap current fraction \( f_{BS} \) is 0.33, and the noninductive current fraction is 0.76, with \( H_{98}(y, 2) = 1.05 \). The central ion and electron temperature are 9.2 keV and 8.4 keV, respectively. Figure 8 shows the parameter profiles of the H1 regime and the evolution of the main plasma parameters is shown in figure 9.

H1 of table 4 shows the high plasma current operation capability of the hybrid scenario in HL-2M and it requires maximum NBI power. An alternative scenario is also investigated at lower NBI power requirements as shown in table 4 H2. The plasma current is chosen around 1 MA, with \( B_t = 2.0 \) T and \( a = 0.55 \) m. The ramp-up rate of the plasma current is set as 2 MA s\(^{-1}\), taking 0.5 s to achieve the flat-top. Two ECRH launchers (\( X_{ecrh1} = 0.4 \), \( X_{ecrh2} = 0.2 \)) are implemented to obtain the flat \( q \) profile around 1. The flat region from \( q_0 \) to \( q_{min} \) is \( \rho = 0 \)–0.4. The powers of NBI, ECRH1 and ECRH2 are 6 MW, 7 MW and 1 MW, respectively. \( \beta_f \) can reach 2.5, with the bootstrap current fraction \( f_{BS} \) = 0.40 and the noninductive current fraction \( f_{ni} \) = 0.86. The central ion and electron temperatures are 6.1 keV and 6.7 keV, respectively. The parameter profiles of the H2 regime are shown in figure 10.

It is known to be difficult for LH to deposit deeply into plasma with a relatively high plasma density. However, even with shallow plasma deposits, the total inductive current of the LH drive current still decreases, making the hybrid regime easier to reach. Implementing LHCD can be considered as an alternative for the hybrid regime implemented by ECCD only. In the same plasma parameters as H2 of table 4, the hybrid regime can also be reached with LHCD, as shown in H3 of table 4. Because of the limitation of METIS when LH is implemented, only one ECCD launcher can be used. Here, the EC deposition width is set as \( \rho = 0.2 \) with the deposition location \( X_{ecrh1} = 0.28 \), assuming two ECCD launchers are used. The powers of LH (deposition location \( X_{bh} = 0.7 \), deposition width is set as \( \rho = 0.2 \)), ECCD and NBI are 3 MA, 6 MW and 6 MW respectively. The \( \beta_f \) can reach 2.4, the bootstrap current fraction \( f_{BS} \) is 0.41, and the noninductive current fraction is 0.89, with \( H_{98}(y, 2) \) = 1.03. The central ion and electron temperatures are 5.8 keV and 6.5 keV, respectively. The parameter profiles of the H3 regime are shown in figure 11.

In addition to the off-axis current drive, confinement is the other important element for driving the hybrid regime. Figure 12 shows that under parameters of \( a = 0.55 \) m, \( f_G = 0.5 \), \( I_p (MA)/B_t (T) = 0.5 \), in order to keep constant \( q_{min} \), with the same additional heating power as H2, a higher enhancement
Figure 9. (a) The waveform of the plasma current $I_p$, the bootstrap current $I_{\text{boot}}$, the non-inductive current $I_{\text{ni}}$, the NB drive current $I_{\text{nbcd}}$, the EC drive current $I_{\text{eccd}}$; (b) the evolution of $4\nu$, $\beta_N$ and $\beta_p$. (c) the waveform of the additional heating power (the first ECCD $P_{\text{eccd1}}$, the second ECCD $P_{\text{eccd2}}$, NB $P_{\text{nb}}$).

Figure 10. The parameter profiles of the H2 regime. (a) $t_{\text{ip}}$: the ion temperature profile, $t_{\text{ep}}$: the electron temperature profile, $n_{\text{ep}}$: the density profile; (b) $j_p$: the total current profile, $j_{\text{ni}}$: the noninductive current profile, $j_{\text{nbicd}}$: the NBI drive current profile, $j_{\text{eccd1}}$: the ECCD1 drive current profile, $j_{\text{eccd2}}$: the ECCD2 drive current profile, $I_{\text{boot}}$: the bootstrap current profile; (c) the diffusion coefficient; (d) the $q$ profile.
factor $H_{98}(y,2)$ is required to reach the hybrid regime (the $q$ profile is still flat with $q_0 \sim 1$) in a higher plasma current $I_p$. The increase of $H_{98}(y,2)$ required has a linear relationship with the increase of $I_p$. However, $\beta_N$ is not obviously increased as the plasma thermal energy increases due to the necessity of keeping a fixed $q$ profile. This shows that having enough input power is essential for obtaining high $\beta_N$ plasmas in the hybrid domain.

### 4.4. Full noninductive regime

In order to explore the steady-state scenario in HL-2M, two routes have been investigated. One is a plasma with an internal transport barrier (ITB) and a reversed $q$ profile with a very high bootstrap current fraction, another one is an extension of the hybrid scenario to a fully steady state. The second choice has the advantage of avoiding deleterious MHD linked to the strong pressure gradients in the ITB region. Similar to

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**Figure 11.** The parameter profiles of the H3 regime. (a) $t_i$: the ion temperature profile, $t_e$: the electron temperature profile, $n_e$: the density profile; (b) $j$: the total current profile, $j_{ni}$: the noninductive current profile, $j_{nhbc}$: the NBI drive current profile, $j_{ecc1}$: the ECCD1 drive current profile, $j_{ecc2}$: the ECCD2 drive current profile, $j_{boot}$: the bootstrap current profile; (c) the diffusion coefficient; (d) the $q$ profile.

**Figure 12.** The plasma current versus the plasma parameters ($\beta_N$, the plasma thermal energy $W_{th}$, and the confinement enhancement factor $H_{98}(y,2)$) in the hybrid regimes with the same additional heating/current drive.

**Table 5.** The plasma parameters of steady state scenarios.

| Steady state | S1           | S2           | S3           |
|--------------|--------------|--------------|--------------|
| $I_p$ (MA)/$B_t$ (T) | 1.0/1.85    | 1.0/1.8     | 1.2/1.7     |
| $\kappa/\delta$ | 1.8/0.5     | 1.8/0.5     | 1.8/0.5     |
| $a/R$ (m) | 0.65/1.78 | 0.65/1.78 | 0.65/1.78 |
| $f_{\alpha}$ | 0.73         | 0.6           | 0.5          |
| $P_{NBI}/P_{ECHR1}/P_{LH}/P_{ECHR2}$ | 1.5/3.5/4  | 10/6.5/(1) | 10/5.5/(—) |
| $X_{echr1}/X_{echr1}(X_{echr2})$ | 0.45/0.6 | 0.34/(—) | 0.42/(—) |
| $q_{sep}/q_{max}$ | 6.9/3.2 | 6.4/1.1 | 5.1/1.1 |
| $\beta_N$ | 1.9         | 1.6           | 1.8          |
| $\beta_N$ | 3.2/4.2 | 2.6/4.2 | 3.4/4.0 |
| $f_{\alpha}$ | 0.63/1.0 | 0.42/1.0 | 0.55/1.0 |
| $T_{e0}/T_{i0}$ (keV) | 4/4 | 6.5/6.6 | 7.5/12 |
| $T_{ped}/T_{i0}$ (keV) | 0.57/0.35 | 0.81/0.64 | 1.10/0.79 |
| $n_{ped}/n_{sep}(1 \times 10^{19})$ | 3/1.0 | 1.9/0.93 | 2.8/0.93 |
| $p_{ped}$ (pa) | $4.3 \times 10^3$ | $4.4 \times 10^3$ | $8.1 \times 10^4$ |
| $W_{th}$ (MJ) | 0.95 | 0.84 | 1.3 |
| $H_{98}(y,2)$ | 1.3        | 1.1           | 1.3          |
Figure 13. The parameter profiles of the S1 regime. (a) $t_i$: the ion temperature profile, $t_e$: the electron temperature profile, $n_{eg}$: the density profile; (b) $j$: the total current profile, $J_{ni}$: noninductive current profile, $J_{nbicd}$: the NBI drive current profile, $J_{eccd}$: the EC drive current profile, $J_{lhcd}$: the LH drive current profile, $J_{boot}$: the bootstrap current profile; (c) the diffusion coefficient; (d) the $q$ profile.

Figure 14. The parameter profiles of the S2 regime. (a) $t_i$: the ion temperature profile, $t_e$: the electron temperature profile, $n_{eg}$: the density profile; (b) $j$: the total current profile, $J_{ni}$: noninductive current profile, $J_{nbicd}$: the NBI drive current profile, $J_{eccd}$: the total ECCD drive current profile, $J_{boot}$: the bootstrap current profile; (c) the diffusion coefficient; (d) the $q$ profile.
section 4.3, Angioni’s scaling law is used to predict the density profile. For an optimum steady-state scenario with a reversed shear profile it would be desirable for $q_{\text{min}}$ to be higher than 2 to avoid the development of the neo-classical tearing mode (NTM). For this purpose, it is necessary to implement enough off-axis current drive to allow $q_{95}$ not to be too high (normally less than 8). In HL-2M, the high power of the NBI on-axis makes it difficult to drive a reversed shear profile due to the deleterious effect of the on-axis current drive [22]. To realize the reversed shear regime of the steady state in HL-2M, enough off-axis current drive with a small amount of on-axis NBI power is implemented, as shown in table 5 S1, and figure 13. Then, 3.5 MW ECCD + 4 MW LHCD + 1.5 MW NBCD make $q_{\text{PS}} > 3$ with $q_{\text{min}} > 2$ for $I_p = 1$ MA and $B_t = 1.85$ T. The ITB is generated due to the reversed shear and $f_{\text{BS}}$ can reach 63% with $H_{98}(y,2) = 1.3$. However, due to the low central heating, $\beta_N$ is 2.3. For a more precise study, the on-axis second ECRH without ECCD for increasing $\beta_N$ in the reversed shear regime will be investigated by CRONOS (which includes a ray-tracing module for EC waves) in the next step of the work.

To reach a high $\beta_N$, the steady state scenario with a hybrid regime $q$-profile characteristic [10, 41] seems to be an alternative, as shown in table 5 S2 and S3. For the low peaked central density profile, like that considered in section 4.3 (figure 14 and S2), the hybrid steady state regime can be reached for $I_p = 1.0$ MA, $B_t = 1.8$ T, $f_\text{G} = 0.6$. The 10 MW NBI combined with two ECRH sources (6.5 MW $X_{\text{ech1}} = 0.34$, 1 MW $X_{\text{ech2}} = 0.15$) are implemented. $\beta_N$ can reach 2.6 with a full noninductive current drive fraction $f_{\text{ni}} = 1$. The central ion

![Figure 15](image-url) Figure 15. The parameter profiles of the S3 regime. (a) $t_{\text{ip}}$: the ion temperature profile, $t_{\text{ep}}$: the electron temperature profile, $n_{\text{ep}}$: the density profile; (b) $j$: the total current profile, $j_{\text{ni}}$: the noninductive current profile, $j_{\text{nbicd}}$: the NBI drive current profile, $j_{\text{eccd}}$: the ECCD drive current profile, $j_{\text{boot}}$: the bootstrap current profile; (c) the diffusion coefficient; (d) the $q$ profile.

![Figure 16](image-url) Figure 16. A profile comparison between METIS and CRONOS. (a) The solid lines are the electron, ion and density profiles of CRONOS simulation, respectively; the dashed lines are the electron, ion and density profiles of the METIS simulation, respectively. (b) The solid lines are the total plasma current and the bootstrap current profiles of the CRONOS simulation, the dashed lines are the total plasma current and the bootstrap current profiles of METIS simulation. (c) The solid lines are the safety factor $q$ profile of the CRONOS simulation, the dashed line is the safety factor $q$ profile of the METIS simulation.
and electron temperatures are 6.6 keV and 6.5 keV, respectively. The $q$ profile is quite flat in the region $0 < \rho < 0.4$ with $\mathcal{H}_{06}(y,2) = 1.1$.

In addition, a more central peaked density profile, as shown in figure 15(a), is used for the hybrid steady state regime simulation. A more peaked central density leads to a higher bootstrap current fraction, which allows the hybrid steady state regime to be driven at a higher plasma current $I_p = 1.2$ MA.

The 10 MW NBI and 5.5 MW ECCD sources are implemented. The flat $q \sim 1$ region is quite wide, around $\rho = 0$–0.5. An internal transport barrier is generated, leading to better confinement: $\beta_N$ reaches 3.4 with $\mathcal{H}_{06}(y,2) = 1.3$ and the ion temperature reaches 12 keV, as shown in tables 5 and S3. The thermal energy of the plasma is 1.2 MJ. The bootstrap current fraction $f_{BS}$ reaches 55%. Therefore, a more central peaked $n_e$ profile is beneficial for the hybrid steady state at a higher plasma current.

5. Detailed ECCD calculations with CRONOS

Several assumptions made in METIS may affect the scenarios found in previous sections. In particular, for the hybrid scenario, since the equilibrium in METIS is solved by using the moments of the Grad–Shafranov equation, and the current diffusion equation is solved with simplified expressions of the current sources, the $q$ profile may change when using more realistic models. This could be particularly important for the high $\beta_N$ scenario simulations where the Shafranov-shift is significant. Therefore, the reference hybrid scenario (table 4 H2) simulated with METIS is additionally simulated using the 1.5D integrated modeling code—CRONOS—for the assessment of the $q$ profile shape and the ECCD obtained from the HL-2M ECRH/ECCD system.

As a first step, a purely current diffusion simulation (including a time evolving equilibrium) has been carried out by taking the ion, the electron temperature and density profiles, as well as the main plasma parameters (the equilibrium boundary, the waveform of the plasma current, additional power, the toroidal field, the effective charge, the line averaged density, etc) from the METIS simulation. The CRONOS simulation results show that the 95% last closed flux surface moves outboard, causing $q_{95}$ to increase to 5.5 ($q_{95} = 4.8$ in METIS). $\beta_N$ is 2.6 and the bootstrap current fraction $f_{BS}$ increases to 44%; meanwhile, the noninductive current fraction increases to 90%. The $q_0$ is slightly higher than that in METIS. The flat region around 1 is $\rho = 0$–0.5, as shown in figure 16. These differences are mainly due to the difference in the equilibrium calculation, the bootstrap current models (using NCLASS [39] in CRONOS) and the number of radial points used in both codes. This has significant consequences for the bootstrap current at the edge, which increases with respect to the one obtained in METIS.

The second step is the assessment of the ECCD with the ray-tracing REMA code [42]. For driving the flat $q \sim 1$ profile, two ECRH launchers are implemented. The frequency and the wave mode of the ECRF gyrotrons used is the 105 GHz and the X-mode. The poloidal and toroidal angles of the mirror of the equatorial launcher are $-10^\circ$ and $10^\circ$, respectively, and those of the upper launcher are $-50^\circ$ and $10^\circ$, respectively. The powers of the equatorial and of the upper launcher are 4.0 MW and 2.0 MW. The ray trajectories are shown in figures 17(a) and (b). In this case, the maximum deposition location of the

Figure 17. The ray trajectory of ECRF. (a) the trajectory in the poloidal direction of the equatorial EC antenna EC1 and the upper EC antenna EC2, (b) the trajectory in the toroidal direction of EC1 and EC2. The $X$–$Y$ coordinate system is from the top view of the tokamak. (c) The power absorption fraction profile of EC1 and EC2, (d) the power deposition profile of EC1 and EC2.
EC power is around $\rho = 0.3$. The definition of the quantities $\eta$ shown in figure 17(c) used in REMA is as follows:

$$\eta(\rho) = 1 - \exp\left(-\int_0^{s(\rho)} \alpha(s) \, ds\right)$$

where $s$ is the coordinate along the ray trajectory and $\alpha$ is the EC wave local absorption coefficient. Then $\eta$ varies between 0 (as the wave enters the plasma) to the total fraction of absorbed power as the ray exits the plasma (1 for EC1 and ~0.9 for EC2). It is a multi-valued function of $\rho$ because the ray can cross a given flux surface more than once (twice in this case). The position in which $\eta$ undergoes a strong variation corresponds to the location of strong absorption ($\rho \sim 0.3$ and $\rho \sim 0.4$ for EC1 and EC2, respectively), as also evident in figure 17(d). The safety factor of 95% for the last closed flux surface is 5.4. The $\beta_S$ is 2.6 ($4I_1$ is 3.6), and the bootstrap current fraction $f_{\text{BS}}$ is 44%; meanwhile, the noninductive current fraction is around 74%. The flat region of the $q$ profile is quite wide between $\rho = 0.4$, with $q_{\min} = 0.89$ and $q_0 = 0.9$. The total EC drive current simulated by REMA is 0.15 MA. The localized narrower and more peaked EC driven current causes the $q_{\min}$ to be slightly lower, as shown in figure 18. However, in general, the $q$ profile keeps an acceptable shape for a typical hybrid scenario and it is comparable to the $q$ profile obtained with METIS.

6. Summary

The operation scenarios (conventional inductive, hybrid, steady state) of the new medium-sized tokamak HL-2M are systematically analyzed 0.5D more quickly than with the real-time scenario simulation code METIS. For the baseline, a central electron temperature of more than 10 keV can be achieved with 27 MW full addition heating power for $I_p = 3$ MA and $f_G = 0.65$. In this case, the thermal energy and $\beta_N$ can reach 5 MJ and 2.5, respectively. To sustain the hybrid discharge, the stabilization method of the $q$ profile is studied. It is observed that inductive current profile diffusion towards the magnetic axis can cause fluctuations of the $q$ profile and enough of a noninductive current fraction can efficiently weaken this.

Meanwhile, controlling the plasma ramp-up rate as well as the additional heating rate is another way to decrease the fluctuation of the $q$ profile. The hybrid regime with $f_{\text{in}} = 80\%–90\%$ can be realized at $I_p = 1–1.4$ MA with an $f_G$ around 0.5 and $\beta_N$ is 2.5–2.9 with $H_{\text{RMS}}(y,2) = 1.1$. Because of the effect of the on-axis NBCD, the hybrid steady state at $I_p = 1.0$ MA and 1.2 MA can be achieved more easily than the steady state regimes with reversed shear, corresponding to $\beta_N = 2.6$ and 2.9.

The results obtained in this paper show that HL-2M is a flexible tokamak able to obtain a broad variety of plasmas due to different combinations of heating and current drive systems—in particular significant electron heating. This is especially important for the correct assessment of future tokamak devices, which, unlike most present-day high-performance plasmas, will be dominated by electron heating due to the alpha power generated by fusion reactions. Therefore, in HL-2M, topics such as turbulence and power exhaust in steady-state scenarios at high $\beta_N$ can be studied in conditions closer to those expected in tokamak reactors. However, a more detailed assessment of HL-2M scenarios is required, in particular for those with strong nonlinearities between the heat and particle transport, as well as the current profile, as is the case for advanced scenarios. The first step in this direction has been taken in this paper by carefully analyzing the requirements in terms of ECCD for the hybrid scenario. From the analysis made with CRONOS, the power installed in HL-2M would be sufficient to drive the required $q$ profile. More detailed predictive simulations involving self-consistent heat and particle transport, pedestal pressure and heating and current drive calculations will be performed in the future.

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