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journal or publication title	IEEE Transactions on Plasma Science
volume	44
number	11
page range	2915-2922
year	2016-10-07
URL	http://hdl.handle.net/10655/00012713

doi: 10.1109/TPS.2016.2613937

Prospects for Self-Burning Operation in Heliotron-Type Fusion Reactor

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Abstract—Possible gaps between the current LHD experiment and the reactor operation have been investigated using the dynamic profile extrapolation model, which is validated by LHD experiments. Self-burning solutions can be achieved under the wide range of fueling conditions. However, the minimum fusion output is rather high and it may be incompatible with the allowable heat load to the in-vessel components. In order to meet the conditions, improvement of the confinement properties or increase of the magnetic field strength is required. In addition, auxiliary heating is one of the effective means for reducing the minimum fusion output by substituting fusion α heating, although this means abandoning the advantage of self-burning capability. Fuel dilution is enhanced due to the source profile effects of the α particle that is generated in the core plasma and fuel which must be injected from the periphery. In order to mitigate the fuel dilution to below an acceptable level, sufficient fuel re-circulation is required even if it leads to reduction of burning efficiency.

I. INTRODUCTION

Since a confinement field is generated by only external coils, a stellarator/heliotron-type fusion reactor has the potential to perform self-burning operation in which plasma is sustained by fusion α output without any auxiliary heating. A significant advantage for the self-burning plasma is minimization of re-circulation power. Furthermore, the net-current free feature of the helical system has an advantage in the adaptability to high-density operation due to the absence of constraints on the current drive and real-time equilibrium control. Since all the plasma heating powers are covered by fusion α output in the self-burning plasma, fueling becomes an essential control means to decide upon an operational point. The controllability of the plasma density becomes increasingly essential for the burning plasma operation in the stellarator/heliotron-type fusion reactor.

A fueling experiment using a solid hydrogen pellet injection has been implemented intensively in the Large Helical Device (LHD), which is a heliotron-type fully superconducting plasma confinement device with a pair of $\ell/m=2/10$ continuous winding helical coils and three pairs of poloidal coils [1]. Global energy confinement time of the stellarator plasmas can be described by the International Stellarator Scalings (ISS04 [2], or ISS95 [3]) which show gyro-Bohm type energy confinement properties. That is, it has positive dependence on density ($\propto n_e^{0.6}$). In order to develop a pellet fueling algorithm in the heliotron-type fusion reactor, a zero-dimensional approach had been employed with the ISS95 scaling [4].

The zero-dimensional model has the advantage of grasping the full picture without using long computing time. At the same time, dynamics of the plasma profile become important for estimating the required pellet injection conditions and precise fueling effects on the burning plasma, e.g., pellet velocity and size, fueling efficiency, and perturbation of fusion output due to the fueling. Therefore, it is necessary to estimate the dynamic of the plasma profile with a one-dimensional model that reduces the computing time as much as possible. An extrapolation method which can estimate the plasma profiles in the steady-state of the burning plasma was developed by assuming gyro-Bohm type parameter dependence [5]. Since this model supposes similarity in the plasma pressure profile between the LHD plasma and the burning plasma, the pressure profile of the burning plasma can be extrapolated directly without consuming much computing time. This extrapolation method has been extended to a dynamic plasma profile analysis taking into account the source profile of the fueling and the diffusive nature of plasma particle confinement [6], [7]. In this study, possible gaps between the current LHD experiment and the reactor operation have been investigated using the above mentioned dynamic profile extrapolation model.

This paper is organized as follows. In section II, the dynamic profile extrapolation model is described and verified with LHD experiment results. In section III, the self-burning plasma is predicted using the verified model, and conceivable gaps between the LHD experiment and the reactor are discussed in section IV.

II. DYNAMIC PROFILE EXTRAPOLATION MODEL

A. Model

In order to predict the burning plasma properties on the basis of the LHD experiments, the direct profile extrapolation (DPE) method [5], in which the normalized plasma pressure profile obtained from the LHD experiment is directly extrapolated into a burning plasma by assuming gyro-Bohm type parameter dependence, has been extended to a dynamic plasma profile analysis. A similar analysis method was adopted in a previous paper [6], but an evaluation method for the particle diffusion coefficient, which impacts the fueling efficiency, has been updated in this paper. The principal justifications for the DPE method are based on the facts that (i) the LHD plasma shows gyro-Bohm type parameter dependence under wide experimental conditions, (ii) the collisionality of the self-burning plasma in a helical reactor ($\nu_b^* \sim 0.1 - 0.4$) is within the range of collisionality in the LHD experimental regime,

Fig. 1. Normalized power dependence of the diffusion coefficient. The symbol and the line denote measured diffusion coefficients in the LHD and the fitted line.

and (iii) the heating power density of the LHD experiments, $0.25 \sim 0.5 \text{ MW/m}^3$, corresponds to that of the self-burning plasma. Density profile changes were expressed by a diffusion equation which assumed that the particle flux consists of the diffusion term $D(r)$ and the convection term $V(r)$. Only pellet fueling is considered as a particle source because it is the only possible solution for injecting particles inside the last closed flux surface under the burning plasma condition at this moment. Although the high field side pellet injection [8] is one of the effective solutions to enhance fueling efficiency in tokamaks, similar improvement of the fueling efficiency has not been observed clearly in LHD. Therefore, a conventional Neutral Gas Shielding (NGS) pellet ablation model [9] has been employed to estimate the particle source profile of the fueling.

Wall recycling, which is sensitive to the wall materials and its conditions, significantly affects the fueling in the present day experiments. Regardless of the wall material and conditions, however, wall recycling will be saturated, i.e., invariable, in the steady state operation phase. In this study, therefore, the wall recycling effect is not treated explicitly, assuming the steady state operation phase. In other words, we assume that a particle exchange between the boundary plasma and recycling particles are implicitly balanced. Pellet injection is considered as only particle source, and the plasma edge is assumed to be a particle sink as a particle pump, which is in counterbalance with the fueling.

Particle confinement properties are investigated in detail using a gas-puff modulation method in LHD [10]. The particle transport coefficients vary according to the magnetic configuration. In the standard configuration in which the magnetic axis position R_{ax} is 3.6 m, diffusion coefficient $D(r)$ is spatially constant, and the absolute value is more than one order higher than a neoclassical transport prediction. This shows that the

particle transport is dominated by anomalous processes. And convection velocity $V(r)$ is almost 0 in the core region. The scaling of the particle transport coefficients have been derived from the density decay after pellet injections. The temporal change of the density profile after pellet fueling is reasonably reproduced by the spatially constant $D(r)$ and near zero $V(r)$ in LHD. The D is enhanced with increasing heating power. The dependence of D on the normalized power ($P/\langle n \rangle$) is plotted by filled circles in Fig. 1. The thick line denotes a fitting line with constraints of gyro-Bohm type confinement that can be expressed by the following equations.

$$D = 2.79 \times 10^7 \left(\frac{P}{\langle n \rangle} \right)^{0.6} B_T^{-0.8} f_R^{-1}, \quad (1)$$

$$V = 0, \quad (2)$$

where B_T and f_R are toroidal magnetic field strength and dimensional scale factor from the LHD, respectively. Once density profile is determined, a stationary solution of a pressure profile can be estimated by the DPE method [11]. On the other hand, since the pressure profile is changing on the time scale of the energy confinement time, a dynamical pressure profile at a given instant should be estimated taking into account the energy confinement time as described in the previous papers [6], [7].

In order to clarify the minimum requirements to control burning plasma, several parameters, which do not require control in real time, are idealized in this study. For example, equilibrium, MHD instability, and high-energy α particle loss are essential for the plasma confinement, but they are not objects of the real-time burning control in the steady-state burning phase in the case of stellarators. They are rather issues of the configuration optimization. Detailed investigation of the α particles confinement of the heliotron reactor shows that the energy loss rate of the alpha particle varies 5 % to 29 % depending on the magnetic configuration, and it strongly depends on the operating density and reaches almost 0 % loss [12].

The other concern is enhancement of neoclassical transport in the low collisionality regime [13]. Since the pressure profile is extrapolated only by supposing the gyro-Bohm type confinement properties in the DPE method, accurate predictions cannot be made if the neoclassical transport becomes a dominant factor in determining the confinement properties. At the least, the operational density will increase in order to compensate for the energy loss enhancement due to the neoclassical transport. The DPE method, therefore, can show the minimum fueling requirements to control burning plasma.

B. Model verification

Adequacy of the above-described model is verified by reproducing the LHD discharge with intensive pellet injections. Fig. 2 is a comparison of waveforms between the LHD experiment and model calculation. Multiple pellets injected in the period between 3.7 s and 4.0 s and the central electron density, $n_e(0)$, increases from 0.2×10^{20} to $2.5 \times 10^{20} \text{ m}^{-3}$ during the pellet

Fig. 2. Comparison of the temporal evolution in an intensive pellet fueled discharge between the LHD experiment and simulation. (a) Central density and temperature, (b) plasma stored energy.

injection sequence, while the central electron temperature, $T_e(0)$, decreases from 2.3 keV to 0.3 keV. After the pellet injection sequence, the temperature recovery is faster than the density relaxation. Therefore, the plasma stored energy continues to increase for 300 ms. The model calculation results agree well with the measurements not only in attainable values but also in a time constant despite the fact that the normalized collisionality, ν_b^* , which is the electron-ion collision frequency normalized by the trapped electron bounce frequency, varies by two orders from 0.2 to 20.

III. SELF-BURNING OPERATION

A. Operational point

As mentioned in the model explanation, sinPDFce the confinement field has a priori been fixed in stellarators, only heat and particle controls are the primary control knobs for the plasma discharges. Therefore, diversity of confinement properties is very narrow and relatively assured extrapolation is expected. Especially in the case of self-burning operation, since the auxiliary heating will be replaced by the fusion α output, particle control, i.e., fueling and exhaust, becomes the only primary control knob for the self-burning operation.

Burning plasma operations have been simulated at the minimum density, which can maintain the self-burning condition,

Fig. 3. Contour plot of required auxiliary heating power to sustain a steady-state burning plasma (green and light blue) and fusion α output (magenta). Red solid line denotes self-burning condition in which no auxiliary heating power is required.

supposing that the FFHR-d1 reactor design [14] in which plasma geometry is four times larger than LHD in the linear dimensions and that magnetic field, B_T , is 5.1 T. Fig. 3 shows typical operational regime in density and temperature space which is estimated from the static heat balance in the burning plasma. The green and the blue contour lines show required auxiliary heating power every 20 MW and surplus power generation every 50 MW. The red thick line, which lies between the green and the blue contour lines, indicates self-burning condition in which heat balance is achieved. The magenta dashed line shows the contour of fusion α output every 200 MW. The self-burning operational point should be on the red thick line, and the fusion α output can be estimated from the intersection between the red thick line and the magenta contour lines. Additionally, the stable operational point is restricted to the higher temperature part in which the gradient of the red thick line is positive. Therefore, the minimum density on the red thick line is the minimum self-burning operational point at which temperature and fusion output are minimized, and the fusion output is increased as the operational density increases.

B. Impact of fueling depth

In order to investigate the impact of pellet fueling conditions on the burning plasma operation, modeled pellet ablation depth profile is assumed to change normalized pellet penetration depth λ/a from 0.3 to 0.9. The pellet size is assumed to be about 5 % of the particles in the background plasma. That is, 2×10^{22} atoms in particle number, in order to mitigate the fusion output variation. Fig. 4 shows the pellet penetration depth dependence of the density and temperature profiles at the minimum fusion output satisfying the self-burning condition. Dashed and solid lines denote profiles before and after pellet ablation, and the differences indicate maximum perturbation

Fig. 4. Density (blue) and temperature (red) profiles just before (dashed line) and after (solid line) pellet fueling under the steady-state self-burning conditions.

with pellet fueling. In the case of $\lambda/a = 0.3$, the density profile inside the pellet deposited radius ($\rho < 0.7$) remains nearly unaffected and flat density profile is formed. The density profile peaks as the pellet penetration depth deepens and the peaking factor, which is defined by $n_e(0)/\bar{n}_e$, becomes 1.52 at $\lambda/a = 0.9$. In contrast, the temperature profile becomes moderately peaked and higher in a shallow pellet penetration.

Effects of the pellet penetration depth on the burning plasma properties under the minimum fusion output conditions are shown in Fig. 5. The self-burning plasma can be sustained in a broad range of penetration depth, and a self-burning solution can be found under the feasible pellet fueling conditions at the current pellet injection technology, such as single-stage pneumatic pipe gun (~ 1500 m/s). The pellet penetration depth affects the self-burning plasma properties through the changing plasma profiles, and the following tendencies are seen as the pellet penetration deepens: (a) central density increase and central temperature decrease, (b) moderation of the minimum fusion output from 1 GW to 700 MW and increase of the burning efficiency, which is defined as a ratio between the burned particles and the fueled particles, from 1.0 to 2.9 %, and (c) reduction of the required fueling rate prolonging the pellet injection interval. It seems reasonable to conclude that the deep fueling into the core plasma leads to preferable burning properties. On the other hand, (d) extremely high pellet injection velocity beyond 10 km/s, which cannot be attained with present-day injection technology, is required to allow the deep pellet fueling. Although use of a larger mass pellet can alleviate the difficulty of high-speed pellet injection, the effect is restricted because the large pellet size may cause unacceptable fusion output variation. Considering the current pellet injection technology, there is still a large gap for the higher velocity pellet injection beyond 1500 m/s with large size $N = 2 \times 10^{22}$ (7.4 mm diameter and length cylinder) and high repetition rate (2–10 Hz). Therefore, plasma confinement

Fig. 5. Dependence of the self-burning plasma parameters on the normalized pellet penetration depth (λ/a).

study under shallow pellet penetration is required in the LHD experiment in order to find a compromise fueling scenario.

IV. CONCEIVABLE GAPS FROM THE LHD EXPERIMENT

A. Optimization of fusion output

In this simulation, the fusion output is rather high ($P_\alpha = 1$ GW @ $\lambda/a = 0.3$) even at minimum output operation. This may be incompatible with heat and particle loads at the divertor and the first wall. And considering the plasma pressure, this may be incompatible because the volume averaged β value, i.e., the ratio of the plasma pressure to the magnetic pressure

Fig. 6. B_T dependence of minimum fusion α output. Top axis indicates equivalent confinement improvement factor. Blue dashed line denotes standard magnetic field strength in this study.

of the confinement field, is estimated to be 7.0 % in this simulation despite the fact that the maximum attainable volume averaged β value is 5.0 % in LHD even at low B_T conditions [15]. Since the operational point of the burning plasma is determined by heat balance between heating power and loss power, improvement of confinement properties to reduce confinement loss and/or adding an auxiliary heating is necessary to reduce plasma pressure and fusion output.

Confinement improvement is one of the most important subjects in fusion plasma research. Much effort has been made in confinement improvement studies, and several confinement improvement modes are found in stellarators [16]–[18]. However, these are not always available in the burning-plasma operation because fusion output is uniquely determined by the plasma profile, and the controllability of the plasma profile is very restricted under realistic fueling conditions. Therefore, it is important to enhance intrinsic confinement properties rather than to find conditional confinement improvements. Increase of magnetic field strength is an obvious solution to enhance intrinsic confinement properties, although this is very difficult due to the technological constraints, i.e., magnetic stored energy, high field critical current density, and electromagnetic force. Based on the gyro-Bohm type confinement, increase of the magnetic field strength is equivalent to enhancement of confinement properties because the energy confinement time is proportional to $B_T^{0.8}$. Fig. 6 shows the magnetic field strength B_T dependence of the minimum fusion α output. The bottom axis and the top axis show the magnetic field strength B_T and the corresponding confinement improvement factor, respectively. The minimum fusion α output can be reduced effectively by increasing the magnetic field strength. If it is possible to increase the magnetic field more than 5.7 T (12.7 %), which is equivalent to 1.1 in the confinement improvement factor, the minimum fusion α output can be reduced to an acceptable level below 600 MW. On the other hand, it must be noted that the increase in the magnetic field leads to the

Fig. 7. Density dependence of fusion α output at the self-burning and the sub-ignition burning with 80 MW auxiliary heating.

increase of the magnetic stored energy and the current density beyond the latest superconducting technology being used for ITER.

Another remaining possibility for confinement property enhancement is isotope effects of fuel on the confinement properties. In fact, a better confinement for a heavier isotope is shown in tokamaks [19], [20] although no distinct isotopic effects are observed in small or medium size stellarators. It will be helpful for designing the reactor if preferable isotope effects are found in the LHD deuterium experiments, which are planned in the near future.

One of the advantageous points of the stellarator/heliotron type reactor is compatibility with the self-burning operation because current drive is not required to generate a confinement field. In order to inject auxiliary heating power, a significant proportion of fusion output must be spent taking into account energy conversion efficiencies (1) from fusion output to electricity, (2) from electricity to heating power, and (3) heating efficiency and/or current drive efficiency. Furthermore, technological difficulties lie ahead for developing the steady-state high-power heating devices. Therefore, it is better to avoid use of the auxiliary heating as much as possible in the case of the stellarator, except for the start-up phase of burning plasma. On the other hand, the auxiliary heating allows reduction of the fusion output by substituting fusion α output. For example, if there is 80 MW auxiliary heating power, the burning plasma condition is relaxed down to the blue dashed line in Fig. 3, and operational density and fusion output is moderate, as shown in Fig. 7.

B. Effect of fuel dilution

Fuel dilution due to the fusion product, namely helium, is one of the most important issues in the burning plasma,

Fig. 8. Effect of helium confinement time on the helium concentration profile under the self-burning conditions with minimum fusion output.

although there are difficulties in a reliable prediction and there is much to study. The helium effect on the fuel dilution can be separated into two components, helium transport in the core plasma and helium transport in the edge plasma. The impurity screening effect is predicted in the edge stochastic layer of helical systems, which surround the core plasma. A divertor modeling study suggests that the impurity influx is reduced significantly by the friction force from the plasma flow along the field lines in the edge stochastic layer under high-density conditions [21], and this effect has been confirmed experimentally in the LHD [22]. Therefore, recycling effects of the helium particles on the core plasma will be reduced under the high-density condition in which the impurity screening effect is dominant.

The helium effects on the core plasma dilution are a fundamental problem in burning plasma, though it does not appear in present-day experiments. Helium generation and hydrogen isotopes consumption are continued simultaneously in the core plasma during burning plasma operation. Conversely, feasible fueling is restricted to the peripheral region of the core plasma, as mentioned in section III-B. Therefore, fuel dilution cannot be compensated by the refueling directly. It must be compensated through a transport of helium and fuel particles indirectly. This fact leads to peaked helium profile compared to the global particle balance estimation.

In order to make a rough estimate of the fuel dilution effects on the core plasma, self-burning simulation is carried out varying the ratio of a helium confinement time to a bulk plasma (hydrogen isotope) confinement time. Helium transport is independently calculated by using the same diffusion equation with the bulk plasma. The helium particle source profile is given by the fusion reaction profile, and the ratio of the helium confinement time to a bulk plasma confinement time was varied between 0.5 and 5. Here, the shallow pellet fueling

Fig. 9. Effect of helium confinement time on (a) the fuel dilution ratio, and (b) central density and temperature at minimum fusion output.

condition ($\lambda/a = 0.3$) with realistic pellet velocity is assumed. Therefore, density profile of the background plasma is flat and burning efficiency is around 1 %, as shown in Fig. 5.

With increasing helium confinement time, helium concentration is increased, as shown in Fig. 8, and operational density of the background plasma is also increased to compensate for a reduction of effective fuel density while maintaining the steady temperature profile, as shown in Fig. 9. It must be noted that the central fuel dilution (2.5 %) is higher than the burning efficiency (~ 1 %) even in the enhanced helium diffusion case ($\tau_{\text{He}} = 0.5\tau_{\text{H}}$), and the central fuel dilution reaches to 20 % if the helium confinement is five times higher than bulk plasma ($\tau_{\text{He}} = 5\tau_{\text{H}}$). The difficulties with the fuel dilution are mainly concerned with increase of operational density, namely (1) increase of required fueling and (2) higher β operation, while increase of Z_{eff} is not a significant problem, and is only 1.14 even in the case of $\tau_{\text{He}}/\tau_{\text{H}} = 5$. Further investigation is necessary for more precise predictions taking into account the helium particle source profile broadening during a slowing down process and interactions between the helium and bulk plasma transport.

From the above mentioned results, it is clear that the burning efficiency, which is directly related to the helium generation, should be reduced in order to maintain an acceptable fuel dilution level by injecting sufficient amounts of fuel. The reduction of the burning efficiency could lead to the increase in the tritium inventory by increasing the fuel re-circulation. In order to minimize the tritium inventory, one of the possible options is to inject only 50:50 D-T ratio fuel into the plasma vacuum vessel. Then fuel can re-circulate directly after removing only impurities without the isotope separation process, which requires a long time and causes the large tritium

inventory [6], [23].

C. Particle balance

As explained in section IV-B, continuous fueling is mandatory in order to maintain steady-state burning plasma. In order to achieve a steady-state condition, it is inevitable to keep an inclusive particle balance in the plasma vacuum vessel. Therefore, adequate particle exhaust function is required as a counterpart of the fueling. However, there are very few candidates for the vacuum pumping system for a reactor at this moment, due to the difficulties in high throughput steady-state vacuum pumping under the severe environment of the magnetic field and neutron irradiation. One of the promising vacuum pumping concepts, namely, a vapor diffusion pump as primary pump together with a metal foil pump for hydrogen separation, and a liquid metal ring pump as roughing pump, has been delineated by C. Day et al. [24].

In this study, the effects of the wall recycling, which are caused by plasma-wall material interactions (PWI), have not been treated explicitly assuming a steady-state condition. The wall recycling, however, has potential for enormous impact on the plasma operation bringing an uncontrollable particle outgassing from the plasma facing materials (PFM) under the non-steady conditions. In fact, it is shown that the major part of particle balance is governed by wall pumping and only 10 % of the fueled particles are exhausted by vacuum pumps in the LHD, which has the carbon divertor and the metallic first-wall (austenitic stainless steel) [25], [26]. The carbon deposition layer, which originates in the eroded carbon from the divertor, acts as a major trapping site for plasma particles on the first-wall surface [27], therefore, wall-pumping effects are significant even at the metallic first-wall in LHD. In the reactor, on the other hand, the wall pumping will be suppressed because all PFM will be tungsten and the operating temperature will be too high (500 °C at the first wall and > 1000 °C at the divertor) to trap implanted hydrogen [28]. Even for the metallic PFM, however, long-term retention is uncertain due to the growth of the metallic co-deposition layer by plasma exposure and the material damages by neutron irradiation under the steady-state burning plasma condition [29], [30].

Another concern about PWI is the effects of helium particle irradiation. Previous research has shown that the strong hydrogen trapping must be associated with the helium bubbles, and the helium bubbles trap hydrogen up to 577 °C [31]. On the contrary, another experiment shows a significant reduction of the hydrogen retention in tungsten with the He-seeded hydrogen plasma exposure [32]. Since the wall materials will be used under the environment involving helium irradiation owing to fusion α product, there is room for further investigation of the helium effect on hydrogen recycling. The hydrogen/helium mixture plasma exposure experiments are now being conducted in LHD employing the retractive material probes, which can insert samples close to the LHD plasma [33].

Further, various wall conditioning methods, which utilize the PWI related phenomena, have been actively adopted for improving the plasma performance by controlling the particle

recycling in the current experimental devices [34]. However, the steady-state burning plasma is in a completely different situation from the above-mentioned current experiments, i.e., temporary wall conditioning effects cannot play a significant role.

The above-mentioned differences between current experiments and the reactor make it difficult to predict particle balance in the reactor.

V. CONCLUSION

Self-burning plasma has been extrapolated from the LHD experiments taking into account a dynamic behavior of the evolution of the plasma profiles. Possible self-burning solutions can be found under the feasible pellet fueling conditions at the current pellet injection technology. A deep fueling into the core plasma contributes to the efficiency improvement of the fueling and the burning, although it will be necessary to inject pellets at a very high speed (> 10 km/s), which cannot be achieved without pushing past the limit of the current pellet injection technology. In the LHD experiments, it will be necessary to show the sustainment of high performance plasma with very shallow pellet penetration depth that is comparable to the reactor fueling.

The plasma β which is extrapolated in this study exceeds the allowable level observed in the LHD experiments. In order to resolve the discrepancy, there are three possible options: (1) plasma confinement improvement; (2) higher magnetic field operation; and (3) employment of auxiliary heating. The LHD experiments expected to contribute to the first item with investigations of isotope effects in the deuterium experiments are planned for the near future.

Fuel dilution is enhanced due to the source profile effects of the α particle that is generated in the core plasma and the fuel which must be injected from the periphery. In order to mitigate fuel dilution to below an acceptable level, sufficient fuel re-circulation is required even if it leads to reduction of burning efficiency. The low burning efficiency implies the large re-circulation of D-T fuel. In order to minimize the tritium inventory, it is necessary to inject only 50:50 D-T ratio fuel into the plasma vacuum vessel. Then fuel can re-circulate directly following removal of some impurities, and the isotope separation process, which requires a long period of time and causes the large tritium inventory, can be minimized.

In the reactor, fueled particles should be balanced with exhausted particles, and any small ratio of the unsaturated wall pumping components cannot be allowed with regard to the tritium inventory. In order to bridge the gap in the wall pumping effects, there is room for further investigation of the plasma-wall interaction, including helium effects on hydrogen recycling.

ACKNOWLEDGMENTS

The authors are grateful to the members of the LHD project and the Fusion Engineering Research project of the National Institute for Fusion Science for their valuable comments and advice. This work is supported by the Ministry of Education, Sports, Culture, Science and Technology Grants-in-Aid for Scientific Research (S) 20226018.

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