Importance of Helical Pitch Parameter in LHD-type Heliotron Reactor Designs

T. Goto, Y. Suzuki, N. Yanagi, K. Y. Watanabe, S. Imagawa, A. Sagara

National Institute for Fusion Science, Gifu, Japan

e-mail contact of main author: goto.takuya@LHD.nifs.ac.jp

Abstract. In the design studies of the LHD-type heliotron reactors, one of the key issues is to secure sufficient blanket spaces. In this respect, helical pitch parameter γ is quite important because it significantly affects both the coil and plasma shapes. In order to understand the effect of helical pitch parameter on the design window quantitatively, a system design code for the LHD-type heliotron reactors has been developed and parametric scans were carried out with 3 cases of γ=1.15, 1.20 and 1.25. It becomes clear that the possible design window of heliotron reactors strongly depends on the engineering constraints: stored magnetic energy of coil system, blanket space, and neutron wall load. γ = 1.20 is optimum from the viewpoint of moderating the physics requirements, but γ = 1.15 has a robustness to the change in the physics and engineering conditions. Since the design windows are quite sensitive to the engineering constraints and physics conditions, the further detailed study on design feasibility of advanced engineering components and the effect of γ on the physics conditions is expected to optimize the value of γ.

1. Introduction

Helical systems with net-current free plasma essentially have suitable properties as a DEMO and a commercial fusion reactor. There are no disruptive events in net-current free plasmas, resulting in the easiness in a steady-state operation. There is no need for the current drive power, leading to the increase in the plant efficiency. In particular, the Large Helical Device (LHD), which is a heliotron-type system with two continuous helical coils, has several remarkable achievements including high-beta (volume-averaged beta value $<\beta>$ > 5.0 %) discharges and extremely high core density ($n_{e0} > 10^{21}$ m^{-3}) discharges [1]. Based on these achievements, a conceptual design of the LHD-type heliotron fusion reactor, FFHR (Force Free Helical Reactor) [2], has been advanced. One of the critical issues in the design of the LHD-type heliotron reactors is to secure the sufficient space for the blanket. Figure 1 show the poloidal cross-sections of coils and magnetic surfaces in vacuum including ergodized layers at which the nested surfaces show a vertically-elongated shape. Since these ergodized layers are considered to play an important role on particle confinement, magnetic surfaces including these ergodized layers needs to be considered as a plasma confinement region. The space between the helical coils and the plasma confinement region has its minimum at the inboard side of this cross-section. In order to expand the blanket space without changing the size of the reactor, a control of the cross-sectional shape of the magnetic surfaces is necessary. In the LHD-type heliotron system, there are two methods to control the shape of magnetic surfaces. One is a control of the multipole components of the vertical magnetic field by adjusting the currents of vertical field coils (VFCs). In particular, the dipole component determines the position of the magnetic axis R_{ax}. Outward shift of the magnetic axis expands the space between the inboard helical coil and the last closed flux surface (LCFS). However, the closest point in the ergodized layers to the inboard helical coil does not move so much with the outward shift of R_{ax}. Since the volume enclosed by the LCFS shrinks with the outward shift of R_{ax}, it leads to the degradation of the plasma confinement performance. On the other hand, it was found that the ergodized layers play an important role on the confinement of alpha particles [2] and the interference between blanket and ergodized layers should be avoided.

Therefore, the outward shift of R_{ax} is not an effective method. In contrast, helical pitch parameter γ has a relatively large effect on the expansion of the blanket space. Helical pitch parameter is defined as $\gamma = ma_c/lR_c$, where m, l, a_c, and R_c are toroidal pitch number, poloidal pitch number, minor radius, and major radius of helical coil(s), respectively. In the LHD-type (l = 2, m = 10) heliotron system, γ corresponds to the inverse aspect ratio of the helical coils (a_c/R_c). Therefore, a_c decreases with the decrease of γ if R_c is kept constant. But the cross-sectional area of the magnetic surfaces including ergodized layeres decreases more, and then the blanket space increases with the decrease of γ (see Fig.2). The reduction of γ also leads to the decrease of magnetic hoop force on the helical coils. Therefore, the reduction of γ moderates engineering design requirements. However, the decrease in the volume of the plasma confinement region leads to a degradation of the plasma performance. In this respect, the effect of γ in the designs of the LHD-type heliotron reactors needs to be investigated with a comprehensive standpoint on the overall reactor system. In order to understand the relation between the design parameters quantitatively, a system design code for LHD-type heliotron reactors has been developed and parametric scans were carried out. In the next section, a brief review of the developed system code is given. Section 3 provides the result of parametric scans.

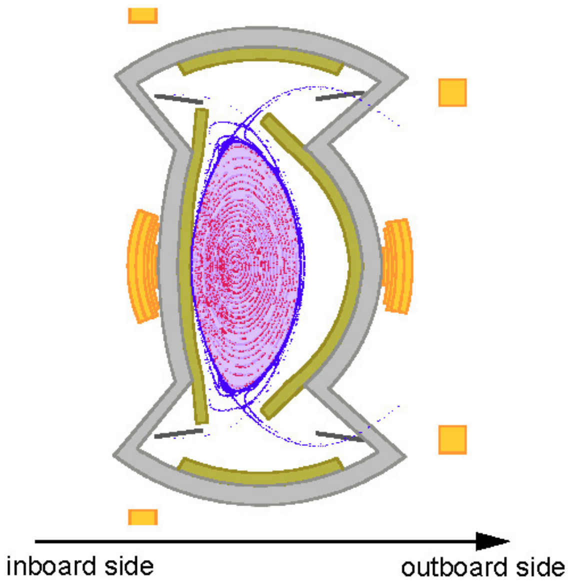

FIG. 1. Cross-sectional view of magnetic surfaces, blankets, shields and coils of the LHD-type heliotron reactor on the cross-section with the minimum blanket space at inboard side.

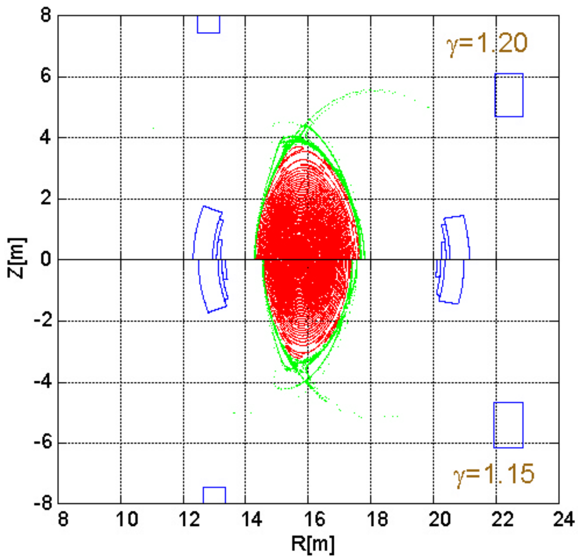

FIG. 2. Comparison of the shapes of the external coils and the magnetic surfaces with the helical pitch parameter γ of 1.20 (upper) and 1.15 (lower).

2. Development of System Design Code for Heliotron Reactors

In the development of a system design code for heliotron reactors, the most important and difficult issue is an evaluation of the shape of the magnetic surfaces. In contrast to tokamak reactors, the shape of magnetic surfaces of heliotron reactors, especially the positions of separatrices, is strongly coupled to the geometry of the external (helical) coil(s). Therefore, the parameters related to the geometric configuration of the magnetic surfaces, which is needed to evaluate the plasma performance in the system code, cannot be given as input parameters but need to be obtained from an equilibrium calculation. The equilibrium calculation, however, is time-consuming and is not compatible with the requirement of the fast calculation (less than 1 sec for one parameter set) for the application on parametric scans over a wide design space.

For this reason, database of the magnetic surface configuration for various shapes of the helical coils with a fixed R_c has been established separately using a field line tracing code and the equilibrium code VMEC [3]. The system code refers that database and applies it to different values of R_c by a similar extension. In the design studies of FFHR, the number of the pairs of the VFCs reduced from 3 (LHD case) to 2 in order to secure large spaces for a maintenance. In this study we also adopted 2 pairs of VFCs. It was found that not only the geometry of helical coils but also that of VFCs significantly affects the geometry of magnetic surfaces including ergodized layers. For this reason, the positions of VFCs were carefully examined for each shape of the helical coils. Generally, VFCs of heliotron reactors are located on the circle the center of which locates on the winding center of helical coils because of the easiness in the placement of the supporting structures. At first the radius of the circle on which the VFCs locate and the positions of VFCs on that circle were determined to suppress the stored magnetic energy and the leakage field at the outside of the torus. However, the field line tracing calculation indicated that the volume of the nested magnetic surfaces was smaller than that of the scale-up of LHD. Thereafter, the positions of VFCs were adjusted to achieve as large volume of the nested surfaces as possible without a large increase in the stored magnetic energy. Figure 3 shows the comparison of the magnetic surface structures in the case of $\gamma = 1.2$ with the original and the modified positions of VFCs.

In heliotron configuration, outward shift of the magnetic axis position with the increase of plasma pressure due to Shafranov shift has been predicted by a theory. Such an outward shift also has been observed in LHD high-beta discharges. The numerical simulations by HINT code [4] have predicted that the volume of the nested surface shrinks with the increase of beta value due to the ergodization of the peripheral region. However, Thomson scattering measurements showed that finite electron temperature exists in the ergodized region [4]. It was shown that the finite-beta equilibrium with almost the same shape of the LCFS as in vacuum can be obtained by applying an appropriate vertical field [5]. Therefore, for simplicity, all equilibrium calculations were carried out with a vacuum condition.

The system code has 3 main parts: engineering design module, physics design module and plant power flow evaluation module. In the engineering design module, the maximum magnetic field on helical coil B_{max} and total stored magnetic energy of the coil system W_{mag} are quite important parameter to evaluate the engineering design feasibility. Since the calculation of B_{max} is time-consuming, the system code evaluates B_{max} using the scaling law [6]. W_{mag} is directly calculated by Neumann's law with a simplified model of coils. The blanket space is calculated as the minimum distance between the point at plasma facing side of the inboard helical coil and the field line in the ergodized layers on equatorial plane. The poloidal cross-sectional shapes of helical coils are calculated considering the current density

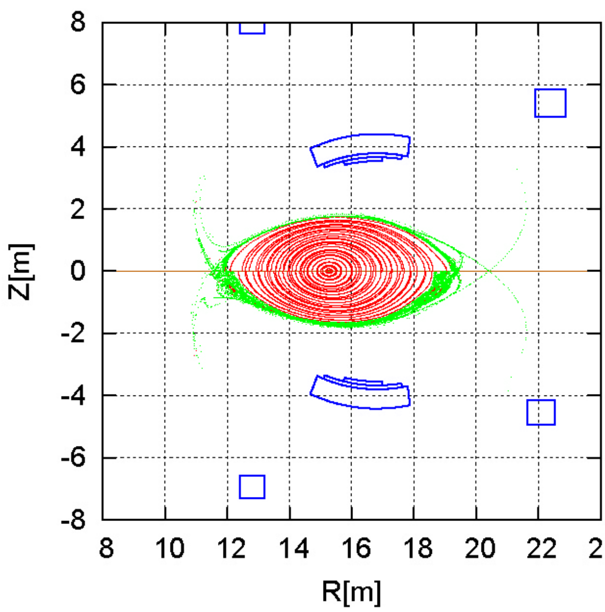

FIG. 3. Comparison of the magnetic surface structure with the original (lower) and the optimized (upper) positions of the vertical field coils.

and width-to-height ratio of helical coils. Consequently, a reasonably accurate evaluation with the short calculation time sufficient for parametric scans can be realized. In the physics design module, the plasma performance is evaluated by the 0-D (volume-averaged) power balance model;

$$\mathrm{d}W_p/\mathrm{d}t = -W_p/\tau_E - P_{\mathrm{rad}} + \eta_\alpha P_\alpha + P_{\mathrm{aux}},$$

where W_p, τ_E, P_{rad}, P_α, P_{aux} and η_α are plasma stored energy, energy confinement time, radiation loss, alpha heating power, auxiliary heating power and alpha heating efficiency, respectively. Temperature and density profiles are described as a power of parabolic function of the normalized minor radius ρ; $T = T_0(1 - \rho^2)^{\alpha_T}$ and $n = n_0(1 - \rho^2)^{\alpha_n}$. The fractions of impurity ions to electrons and alpha heating efficiency are given as input parameters. Confinement property is evaluated using the ISS04v3 scaling [7]. Sudo density limit [8] is considered as a physics constraint. In the plant power flow evaluation module, neutron and thermal load on the first wall and divertor plates, plant thermal output, gross and net electric output are estimated.

3. Parametric Scan

Using the system code, parametric scans were carried out with 3 cases of γ= 1.15, 1.20 and 1.25. In this study, the following 3 engineering constraints were considered: the minimum blanket space Δ, averaged neutron wall loading Γ_{nw}, and stored magnetic energy W_{mag}. According to the neutronics calculations in past design studies, blanket with the thickness of ~1 m is necessary to achieve the sufficient tritium breeding ratio (TBR) over 1.05 and the effective shielding of super-conducting coils from fast (> 0.1 MeV) neutrons for the standard design of Flibe (LiF + BeF2) + Be/JLF-1 and long-life design of the spectral-shifter and tritium breeding (STB) blanket [9]. This blanket concept also requires the neutron wall loading $\Gamma_{\mathrm{nw}} \leq 1.5$ MW/m^2 to suppress the neutron damage of structural materials. On the other hand, the stored magnetic energy of 120-140 GJ is considered to be achieved with a small extension of the engineering base of ITER technology [10] and the achievable maximum value is expected to be 160 GJ. The current density of helical coils is fixed at 25 A/mm^2 throughout this study. Here we adopted an inward-shifted plasma configuration with a ratio between R_{ax} and R_{c} of 3.6/3.9. In LHD, this inward-shifted configuration observes relatively good confinement [7]. Figures 4, 5, and 6 show the design window for the case of γ = 1.25, 1.20, and 1.15, respectively, on the plane with R_{c} and $B_{\mathrm{t,c}}$ (averaged toroidal field at the winding center of the helical coils). Here all design points in the figure has a constant volume-averaged beta value of <β> = 5.5 %. We also assumed the density and temperature profile

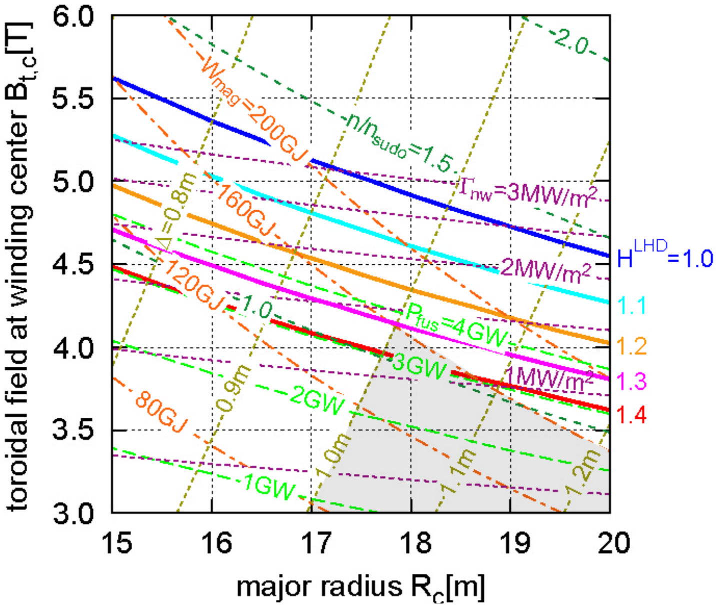

FIG. 4. Contour lines of the design parameters for the case of γ=1.25 and <β> = 5.5 %. The shadowed region corresponds to the design window satisfies all engineering and physics constraints.

factors of $\alpha_n = 0.25$ and $\alpha_T = 0.75$, helium and oxygen ion fraction of 3 % and 0.5 %, respectively In these parametric scans, temperature profile is fixed and then density increases along the vertical axis (proportional to $B_{t,c}^2$). The shadowed regions in the three figures correspond to the design windows that satisfy the all engineering and physics constraints: $\Delta \geq 1.0$ m, $W_{mag} \leq 160$ GJ, $\Gamma_{nw} \leq 1.5$MW/m^2, $n/n_{sudo} \leq 1.5$. The contours of the fusion output P_{fus} and the confinement enhancement factor to LHD experiments H^{LHD} (corresponds to the confinement improvement factor to ISS04v3 scaling with the renormalization factor of f_{ren} = 0.93) are also drawn in these figures. It is clear that the boundary of the design window mainly fixed by the constraints of Δ and W_{mag}. Since these two parameters are the function of engineering parameters only, the possible design window on the R_c-$B_{t,c}$ plane is almost determined by selecting γ. Note that both higher H^{LHD} and the reduction of P_{fus} are required to select a design points locate the lower side of the window. Therefore, the design points on the upper side of the window are favorable from the viewpoint of moderating physics requirements. Apparently, the reduction in γ expands the blanket space. The blanket space in the case of $\gamma = 1.15$ increases by ~ 20 cm compared with the case of $\gamma = 1.25$ at the same R_c. In addition, the stored magnetic energy in the case of $\gamma = 1.25$ is larger than the other two cases with the same values of R_c and $B_{t,c}$. Consequently, no design window with $H^{LHD} < 1.3$ in the case of $\gamma = 1.25$. On the other hand, the design windows for the other two cases spread to the region with smaller H^{LHD} but limited by Γ_{nw}. Although the design window in the R_c- $B_{t,c}$ plane is wider in the case of $\gamma = 1.15$, the achievable minimum W_{mag} does not differ so much compared with the case of $\gamma = 1.20$ and the achievable minimum H^{LHD} is rather large. That is because the averaged minor radius of the

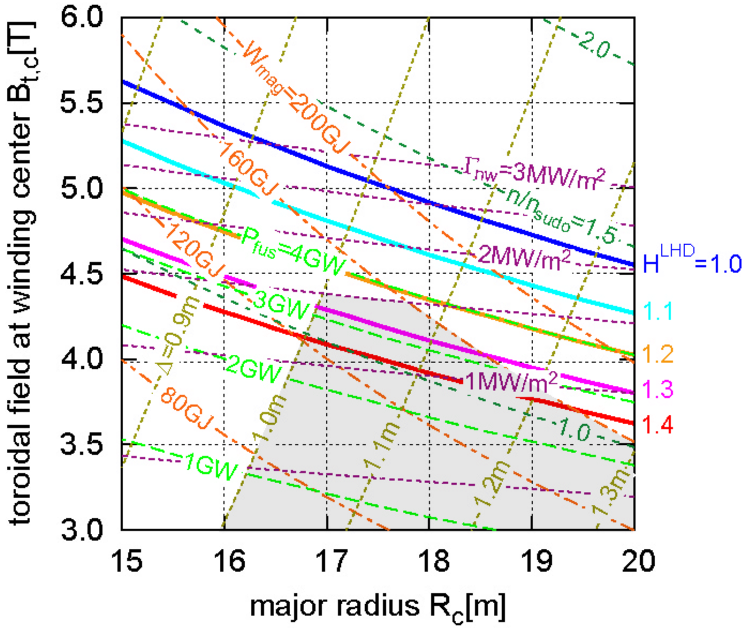

FIG. 5. Contour lines of the design parameters for the case of γ =1.20 and <β> = 5.5 %. The shadowed region corresponds to the design window satisfies all engineering and physics constraints.

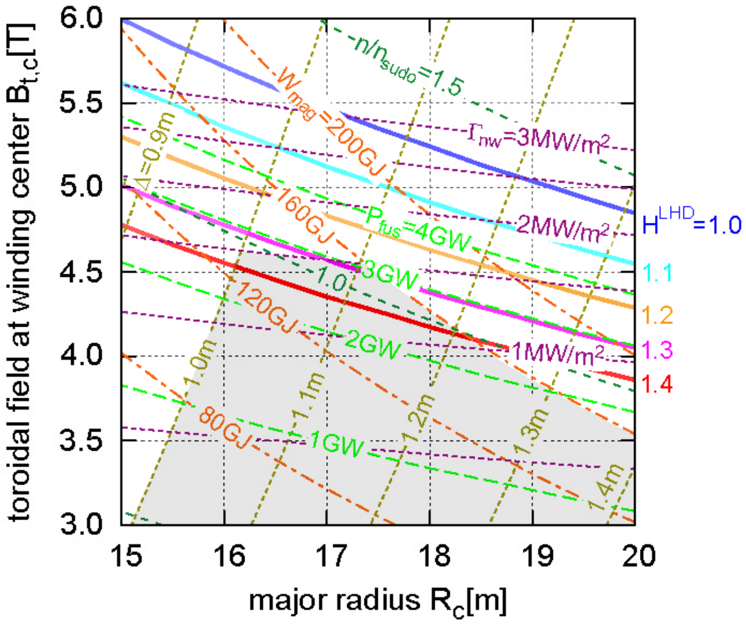

FIG. 6. Contour lines of the design parameters for the case of γ =1.15 and <β> = 5.5 %. The shadowed region corresponds to the design window satisfies all engineering and physics constraints.

LCFS is smaller in the case of $\gamma = 1.15$ with the same R_c. Therefore, the fusion output is also smaller and there is only a limited design window around $R_c \sim 17$ m that satisfies $P_{fus} \sim 3$ GW. ISS04v3 scaling predicts the energy confinement time is proportional to $a^{2.21}R^{0.64}$, where a and R is averaged minor radius and geometric center position of the LCFS. Therefore the reduction in a also leads to the degradation of confinement performance with the same R_c and $B_{t,c}$. (corresponds to the upward shift of the contour lines of H^{LHD}). In this respect, $\gamma = 1.20$ is the optimum selection in the case of $\langle\beta\rangle = 5.5$ %. But the difference in the possible design window between $\gamma = 1.20$ and 1.15 is not so large.

The beta value of $\langle\beta\rangle = 5.5$ % was selected to satisfy $P_{fus} \sim 3$ GW, which is required to achieve the net electric output as large as present commercial power plants (~ 1 GWe). The relation between Γ_{nw} and H^{LHD} varies if the change in the value of P_{fus} is allowed. In the case of the further higher beta value, the contour lines of H^{LHD} shift downward. However, the contour lines of Γ_{nw} show the further downward shift and there is no design window with $H^{LHD} < 1.4$ regardless of the value of γ. On the other hand, there exist design windows with $H^{LHD} < 1.4$ in the case of lower beta value. Figures 7, 8, and 9 show the design window with $\langle\beta\rangle = 4.5$ % for the case of $\gamma = 1.25$, 1.20, and 1.15, respectively. In the case of $\gamma = 1.25$, the design window is almost the same as the higher beta case except the value of the fusion output. Therefore, it is concluded that $H^{LHD} > 1.3$ is necessary to design the LHD-type heliotron reactor with $\gamma = 1.25$ regardless of the value of P_{fus}. In the case of $\gamma = 1.20$ with $\langle\beta\rangle = 4.5$ %, the neutron wall load no longer restricts the design window. But the density limit gives the upper boundary of the design window and it is restricted in the region with $H^{LHD} > 1.3$. In contrast, there is no restriction due to the density limit for the case of $\gamma = 1.15$. Sudo

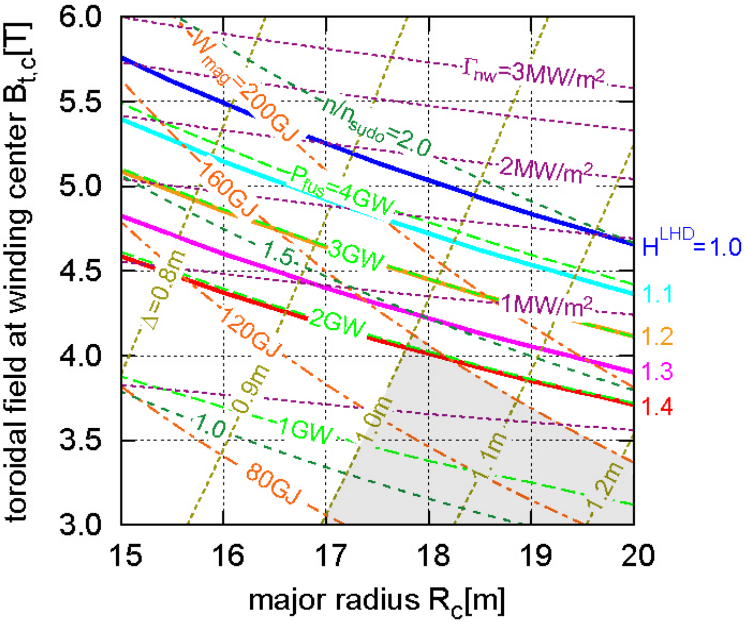

FIG. 7. Contour lines of the design parameters for the case of γ =1.25 and $\langle\beta\rangle$ = 4.5 %. The shadowed region corresponds to the design window satisfies all engineering and physics constraints.

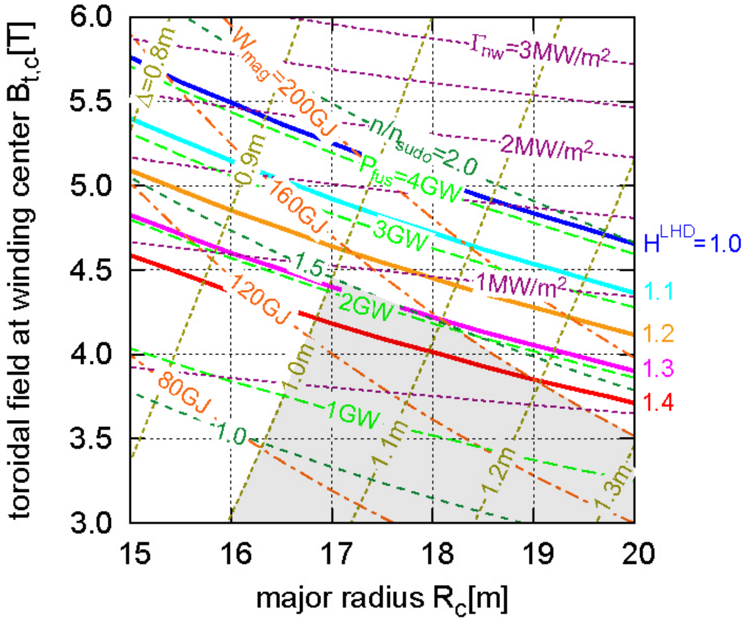

FIG. 8. Contour lines of the design parameters for the case of γ =1.20 and $\langle\beta\rangle$ = 4.5 %. The shadowed region corresponds to the design window satisfies all engineering and physics constraints.

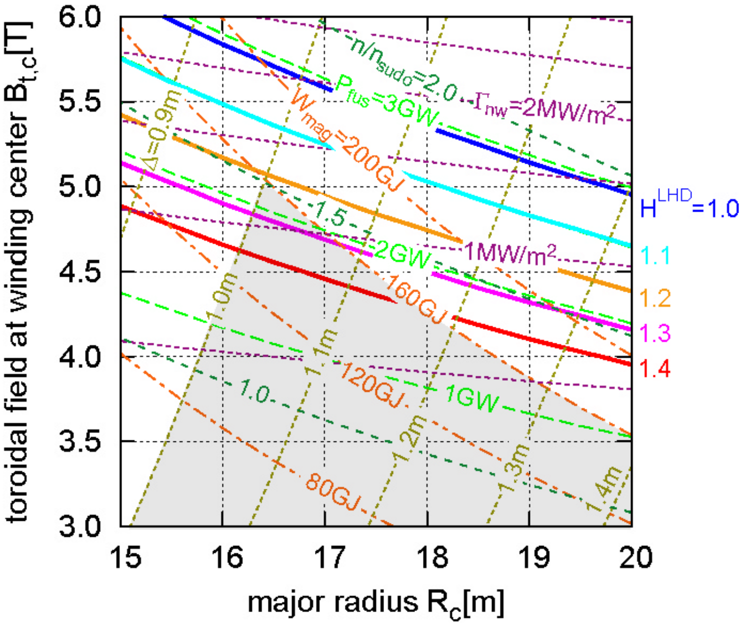

FIG. 9. Contour lines of the design parameters for the case of γ=1.15 and <β> = 4.5 %. The shadowed region corresponds to the design window satisfies all engineering and physics constraints.

density limit is proportional to $(P_{abs}B_{ax}/a^2/R_{ax})^{0.5}$, where B_{ax} is the averaged toroidal field on the magnetic axis. In the case of γ = 1.15, the effect of the decrease in P_{abs} is cancelled out by the decrease of a. Consequently, there is the design window with H^{LHD} ~ 1.2. In this respect, γ = 1.15 is considered to be the optimum selection for P_{fus} ~ 2 GW.

Since the possible design window is quite sensitive to the engineering constraints, a small change in those constraints strongly moderates the physics requirements. In particular, the smaller Δ and higher Γ_{nw} can be achieved by the use of advanced materials (tungsten carbide, vanadium alloy, etc.). As seen in Figs. 5 and 6, the design windows in R_c-$B_{t,c}$ plane expands to the upper direction in the case of <β> = 5.5 % and the required value of H^{LHD} can be reduced if the larger value of Γ_{nw} is allowed. In this respect, further detailed studies on the design feasibility of engineering components (first wall, blanket, and superconducting coils) are required to optimize the γ value. In this study, the same plasma properties (density and temperature profile, fraction of impurity ions, alpha heating efficiency) were considered. If the temperature profile becomes more peaked or density profile becomes less peaked, the restriction of the design window due to the density limit becomes more significant. In such cases, the design with lower γ has the advantage in that it is less affected by the density limit. Although ISS04v3 scaling was used for the evaluation of plasma confinement, the effect of γ is not reflected in the renormalization factor for LHD. If these physics conditions are changed by the change in γ, the optimum value of γ can be varied from the above discussion. Consequently, the effect of γ on both energy and particle confinement also needs to be clarified to deepen the analysis.

4. Conclusion

A system design code for the LHD-type heliotron reactors has been developed and parametric scans were carried out in order to analyze the effect of helical pitch parameter γ on the possible design window. It becomes clear that the design window of the LHD-type heliotron reactor strongly depends on the engineering constraints: blanket space, stored magnetic energy and neutron wall load. In the case of the fusion output of ~ 3 GW, γ = 1.20 is optimum from the viewpoint of moderating the physics requirements. But γ = 1.15 has almost the same design window as γ = 1.20. In the case of the fusion output of ~ 2GW, γ = 1.15 has a largest design window because it is not restricted due to the density limit. Consequently, γ = 1.15 has a robustness to the change in the physics and engineering conditions. The possible design window can be expanded by the progress in the engineering research and development.

Therefore, further detailed study on the design feasibility of engineering components (first wall, blanket, and superconducting coils) is required to optimize the value of γ. The effect of γ on the physics conditions (density and temperature profiles, fractions of impurity ions, alpha heating efficiency, energy and particle confinement properties) also needs to be clarified to deepen the analysis.

Acknowledgements

The authors would appreciate Drs. O. Mitarai, S. Sudo, T. Watanabe, J. Miyazawa, T. Tanaka Y. Kozaki and O. Motojima, and other members of FFHR Design Group for giving valuable comments and advices.

References

[1] KOMORI, A. et al., ''Goal and Achievements of Large Helical Device Project'', Fus. Sci. Technol. **58** (2010) 1.
[2] SAGARA, A. et al., ''Optimization activities on design studies of LHD-type reactor FFHR'', Fus. Eng. Des. **83** (2008) 1690.
[3] HIRSHMAN, S. P. et al., ''Steepest-descent moment method for three-dimensional magnetohydrodynamic equilibria'', Phys. Fluids **26** (1983) 3553.
[4] WATANABE, K. Y. et al., ''Characteristics of MHD Equilibrium and Related Issues on LHD'', Fus. Sci. Technol. **58** (2010) 160.
[5] GOTO, T. et al, ''Core Plasma Design of a Heliotron Reactor'', Contrib. Plasma Phys. **50** (2010) 620.
[6] GOTO, T. et al., ''New Magnetic Scaling for Helitron/Torsatron-type Reactors'', Fus. Sci. Technol. **56** (2009) 925.
[7] YAMADA, H. et al., ''Characterization of energy confinement in net-current free plasmas using the extended International Stellarator Database'', Nucl. Fusion **45** (2005) 1684.
[8] SUDO, S. et al., ''Scalings of Energy Confinement and Density Limit in Stellarator/Heliotron Devices'', Nucl. Fusion **30** (1990) 11.
[9] SAGARA, A. et al., ''Improved structure and long-life blanket concepts for heliotron reactors'', Nucl. Fusion **45** (2005) 258.
[10] IMAGAWA, S. et al., ''Concept of magnet systems for LHD-type reactor'', Nucl. Fusion **49** (2009) 075017.