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LHD-type heliotron reactor design

Based on the physics and engineering achievements of the Large Helical Device (LHD) project [1], conceptual designs of an LHD-type heliotron reactor designated the Force Free Helical Reactor (FFHR) have been advanced. Starting in 1991 [2,3], these studies have been aimed at clarifying the critical issues of core plasma physics and power plant engineering.

One of the critical issues in the design of LHD-type heliotron reactors is to secure sufficient space for the blanket. The blanket space is directly coupled to the helical coil configuration, which affects the core plasma performance and engineering design constraints. To examine these interrelations, a conceptual FFHR-1 system with $l = 3$ (where l is the number of helical coils) was studied. As a more modern successor, we have performed an optimization study mainly focused on blanket space, neutronics performance, a large superconducting magnet system, and plasma operation, based on an LHD-type concept with $l = 2$, $m = 10$, where m is toroidal pitch number. Several ideas have been proposed to create adequate blanket space. In the current design study, a similar extension to reactor size has been considered because recent studies have clarified that the total plant capital cost does not increase so much with an increase in the reactor size when the required confinement improvement is kept constant. Since this enlargement enables increased fusion power with constant neutron wall loading, the cost of electricity (COE) can be reduced. It also enables flexibility in the selection of the magnetic configuration. Therefore, in the current design study, a magnetic configuration that is consistent with LHD high-beta operation has been adopted, resulting in a further reliable extrapolation of LHD achievements.

Candidates to expand blanket space

In helical systems, the space between the plasma and external coils is limited. In an LHD-type heliotron system, this space has its minimum on the poloidal cross-section at which the plasma exhibits a vertically elongated shape, as shown in Fig. 1.

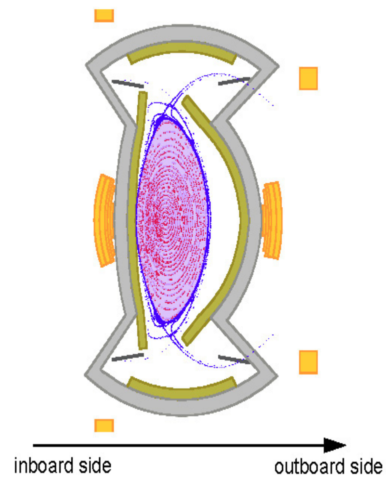

Fig. 1. Cross-sectional view of magnetic surface, blanket, shield, and superconducting coils of an LHD-type heliotron reactor at the cross-section with minimum blanket space at the inboard side.

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On the other hand, neutronics calculations indicate that a blanket with a thickness of ~1 m is necessary to achieve a sufficient tritium breeding ratio (TBR) plus effective shielding of superconducting coils from fast (>0.1 MeV) neutrons. Given these constraints, several methods have been considered to expand the blanket space.

The first one is to control the magnetic surface structure using external coils. Two key parameters determine the magnetic surface structure of a LHD-type heliotron system (LHDHS): the helical pitch parameter γ, and the magnetic axis position R_{ax}. The helical pitch parameter is defined as $\gamma = ma_c/lR_c$, where a_c and R_c are the minor and major radii of the helical coils, respectively. In the case of a LHDHS ($l = 2$, $m = 10$), the helical pitch parameter corresponds to the inverse aspect ratio of the helical coil. Thus, the minor radius of the helical coils decreases with decreasing γ when the major radius is kept constant. But plasma volume also decreases and the space between the coil and plasma increases with decreasing γ. The reduction of γ also leads to a decrease in the magnetic hoop force.

The second parameter, R_{ax}, can be varied by adjusting the vertical field strength by controlling the current in the poloidal coils. Thus, in the design study of FFHR-2, $\gamma = 1.15$, which is smaller than in normal LHD operation ($\gamma = 1.25$), and an outward-shifted configuration ($R_{ax} = R_c$) was selected to expand the blanket space [3]. However, the blanket space at the inboard side is still insufficient because of the interference between the first walls and the ergodic layers of magnetic field lines surrounding the nested flux surfaces. To overcome this problem, a helical X-point divertor (HXD) concept [4] has been proposed.

However, influence of ergodic layers on the confinement of high-energy ions, especially 3.5 MeV alpha particles, has been found to be important in collisionless orbit simulation [5]. Therefore, three alternatives without an HXD have been considered. One is to reduce the shielding thickness only at the inboard side. Neutronics calculations show that the use of advanced materials (e.g., WC) enables the reduction of shield thickness by ~ 0.2 m compared with the standard (B_4C and low-activation ferritic steel JLF-1) case. The second is to improve the symmetry of the magnetic surfaces around the magnetic axis, without shifting the magnetic axis inward, by increasing the current density at the inboard side of the helical coils while decreasing it at the outboard side. Modulation of the current density can be obtained in practice by splitting the helical coils [6]. The third is a photographic enlargement of the reactor size. Since the International Stellarator Scaling (ISS) [7] predicts that the energy confinement time of a helical system is almost proportional to the plasma volume, the magnetic field strength can be reduced for a larger reactor when the required confinement improvement factor is maintained. Thus the stored magnetic energy, which is an index of the total plant capital cost, does not increase so much with reactor size. A larger reactor enables an increase of fusion power at a constant neutron wall loading, resulting in a reduction in COE [8]. This enlargement also enables a flexible selection of magnetic configuration. Consequently, a design concept based on LHD high-beta operation has been proposed.

Consideration of the design point

It is quite important to consider the engineering design feasibility of a large-scale helical coil. The base design for the superconducting magnet system has been proposed using the engineering base of the ITER TF coils as a conventional option. The use of cable-in-conduit conductor (CICC) with Nb_3Al strands has been considered. A stored magnetic energy of 120–140 GJ can be achieved with a small extension of the ITER technology [9], and the achievable maximum value is expected to be 160 GJ. Neutronics calculations indicate that a blanket system with a thickness of ~1 m enables a net TBR above 1.05 for the standard design of Flibe ($LiF + BeF_2$) + Be/JLF-1, as well as a long lifetime for the spectral-shifter and tritium breeding (STB) blanket [3]. In this concept, the average neutron wall loading needs to be reduced to < 1.5 MW/m^2. This 1 m thickness also keeps nuclear heating in the superconducting coils below the cryogenic power limit (less than 1% of fusion power). The fast neutron flux to the superconducting coil is also suppressed to an acceptable level: neutron fluence < 10^{22} n/m^2 for 30 years of operation [8].

In order to find a feasible design window in a quantitative way, parametric scans were carried out over a wide design space by a newly developed system design code for heliotron reactors. This system code can deal with the actual geometry of helical and poloidal coils in the calculation of stored magnetic energy and blanket space. Plasma performance is estimated by a simple volume-averaged (0-D) power balance model. In this case, an inward-shifted configuration ($R_{ax}/R_c = 3.6/3.9$) and $\gamma = 1.2$ were adopted. This configuration is the same one as for LHD high-beta operation (volume-averaged beta ~5% via diamagnetic measurement) [10]. A coil system that basically has a similar shape to that of LHD was considered. However, the minor radius of helical coils was changed to satisfy $\gamma = 1.2$. The width-to-height ratio of helical coils was also set to 2 (larger than that of LHD) to expand the blanket space. The number of pairs of poloidal coils is also reduced from 3 (for LHD) to 2 in order to secure large spaces for maintenance. To calculate plasma confinement properties, physics parameters related to the magnetic configuration are needed. It was found that the magnetic surface structure including the ergodized layers depends strongly on the geometry and the current of not only the helical coils, but also the poloidal coils. Therefore, the system code utilizes the parameters obtained from detailed field line trace calculations of the vacuum equilibrium.

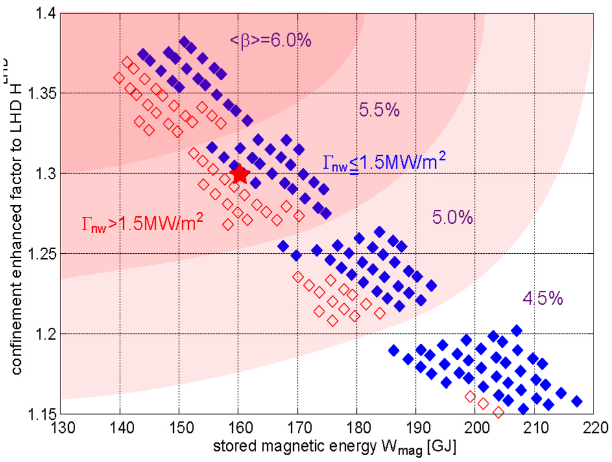

Fig. 2. The stored magnetic energy vs the required energy confinement improvement factor relative to present LHD experiments for design points with fusion power of ~3 GW. The candidate design point is shown as a red star.

Figure 2 shows the relation between the stored magnetic energy W_{mag} and H^{LHD} (the required confinement improvement factor H relative to LHD, which is 0.93 times ISS04v3 scaling [7]) for design points with fusion power ~3 GW. The design point that satisfies both $W_{mag} <$ 160 GJ and average neutron wall load $\Gamma_n < 1.5$ MW/m^2 is found with a volume-average beta value > 5.5% and H^{LHD} > 1.3. Figure 3 shows that the design point with a blanket space ~ 1 m can be found under the same conditions. Therefore, this point (shown as red star in both Figs. 2 and 3) was selected as the candidate. The main design parameters are listed in Table 1.

Table 1. Main design parameters of the selected design point

Coil major/minor radius R_c/a_c [m]	17.0 / 4.08
Plasma major/minor radius R_p/a_p [m]	15.7 / 2.50
Plasma volume V_p [m^3]	1927
Average toroidal field on axis B_{ax} [T]	5.0
Volume-averaged beta value $\langle\beta\rangle$ [%]	5.5
Confinement improvement factor $H^{ISS04v3}$	1.2
Averaged neutron wall load Γ_n [MW/m^2]	1.5
Blanket space Δ [m]	0.985
Stored magnetic energy W_{mag} [GJ]	160

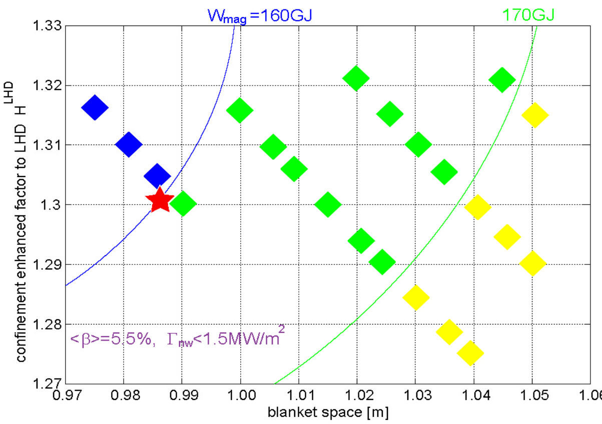

Fig. 3. The blanket space vs the required energy confinement improvement factor relative to present LHD experiments for design points with fusion power ~3 GW and volume-averaged beta of ~5.5%. The candidate design point is shown as a red star.

As mentioned above, the calculation of the system design code is based on parameters related to the magnetic surface structure of vacuum equilibrium. On the other hand, a large Shafranov shift has been observed in LHD high-beta discharges. Shrinking of the nested surface volume due to ergodization of peripheral region is also predicted by numerical simulations with the HINT code [11]. To study this, finite-beta equilibrium calculations were carried out using the VMEC code to examine the self-consistency of the design. These calculations showed that almost the same plasma volume and plasma stored energy as estimated by the system design code can be obtained by adding adequate vertical field which can be done by changing the current of poloidal coils [12].

Consequently, it is concluded that the design of an LHD-type heliotron reactor with sufficient fusion output for commercial operation (~3 GW) is possible with a foreseeable extrapolation of the current physics and engineering achievements.

Conclusion and future work

Based on the physics and engineering achievements of the LHD project, conceptual designs for a LHD-type heliotron reactor FFHR have been proposed. In the current design study, a similar extension of reactor size has been considered as a method to secure sufficient blanket space. This enlargement enables commercial-scale (~ 3 GW) fusion output with a low average neutron wall load (< 1.5 MW/m^2), which enables a long-life blanket concept. It also leads to flexibility in selection of the magnetic configuration, resulting in the adoption of a magnetic configuration consistent with LHD high-beta operation. Consequently, the design of LHD-type helical fusion reactors becomes possible with a foreseeable extrapolation of the current physics and engineering achievements.

Several physics and engineering issues remain to be solved. One of the most critical is the development of the technology for winding a large-scale continuous helical coil. Optimization of the coil system, including the supporting structure and a cooling method, is required. The detailed design of a three-dimensional divertor is also important. Effective fueling and heating of the core plasma to realize steady-state sustainment of a desirable pressure profile is another big issue. Continuous efforts on both experimental and numerical research are enthusiastically expected.

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Remembering Paul Garabedian

Paul R. Garabedian, a leader in the field of computational science, passed away on May 13, 2010, at his home in Manhattan at the age of 82 after a long battle with cancer. During the course of 60 years of research on the faculties at Stanford and New York University (NYU) he maintained an active research program in magnetohydrodynamics (MHD) and computational fluid dynamics, and was one of the premier applied mathematicians of his time.

Fig. 1. Paul R. Garabedian, 8/2/1927–5/13/2010.

Paul (shown in Fig. 1) was born in Cincinnati, Ohio, in 1927. He grew up in an academic family, and did not attend school before setting off for college; his formal education first began as a precocious undergraduate at Brown University, from which he graduated in 1946 [1]. His graduate training was in pure mathematics at Harvard University, where he received his PhD in 1948 in the field of complex analysis [2]. He spent a year teaching at the University of California, Berkeley, followed by nine years on the mathematics faculty at Stanford. During this period Paul made outstanding contributions to the theory of partial differential equations and to problems in the theory of functions of a complex variable. A highlight of his work at this time was his celebrated proof of a special case of an outstanding problem in complex analysis known as the "Bieberbach Conjecture," which he published with Max Schiffer in 1955 [3]. He also served as a Scientific Liaison Officer for the Office of Naval Research in London and led Stanford's research program in hydrodynamic free boundary problems. A noteworthy example is his analysis of the bow shock generated by a blunt body traveling at supersonic velocities [4]. The fluid passing through the shock undergoes substantial heating, and it is necessary to characterize the degree of heating to ensure that the body can sustain these extreme conditions without mechanical failure. Computing the geometry of the shock wave and fluid flow past a given body is an extremely challenging nonlinear problem in partial differential equations. Paul's ingenious solution was to prescribe the shape of the bow wave in advance, and then determine the shape of the body that generated the shock wave and flow field using advanced techniques from the theory of complex variables. He was aided in this work by his first wife, Gladys, who programmed the numerical procedure.

Paul joined the Courant Institute of Mathematical Sciences at NYU in 1959. A few years after his arrival at NYU, Paul's book, *Partial Differential Equations*, was first published [5]. This book is a unique blend of pure and applied mathematics and includes discussions of free boundary problems arising in plasma physics. Paul advised 27 doctoral students in all [6], in addition to a number of master's students and postdoctoral fellows, and was the Director of the Division of Computational Fluid Dynamics at the Courant Institute for 32 years (1978–2010).

During the 1960s and 1970s, Paul and his students and co-workers developed computer codes to study supercritical wing technology as part of the development of aircraft designed to fly near the speed of sound. The basic principle involved concerns the suppression of boundary layer separation by shifting shock waves that occur on the wing toward the trailing edge and making the shock waves as weak as possible. The resulting wing increases lift, fuel efficiency, and the speed of aircraft, and the ideas that flowed from this work influence much of commercial aircraft design today. A NASA Award and a NASA Certificate of Recognition acknowledged this research, which resulted in three books [7,8,9] with longtime collaborator Frances Bauer (whom he met during his undergraduate studies at Brown, while she was a graduate student), former Ph.D. student David Korn, and colleague Antony Jameson.

Paul started working on problems related to fusion energy in the 1970s, using the techniques he had developed for problems in classical fluid dynamics and extending them to study the magnetic confinement problem. He first worked on free boundary models to understand plasma physics experiments carried out at Los Alamos National Laboratory and the Max-Planck Institute for Plasma Physics in Germany. Over the years the sophistication of the plasma modeling tools in Paul's research group grew steadily [10,11,12], resulting in a suite of computer codes used to study plasma equilibrium, transport, and stability. The NSTAB equilibrium code [13] employs a divergencefree representation of the magnetic field that minimizes the magnetic energy using a combination of spectral techniques and finite differences. The stability of the nonlinear equilibrium states is assessed by applying appropriate perturbations to the system and determining whether they lead to multiple steady states that indicate the occurrence of bifurcated solutions. Transport properties of the ions and electrons are estimated by following the orbits of test particles that track the magnetic field lines between particle collisions while maintaining a quasineutrality condition [14]. The codes have been used to design quasiaxisymmetric stellarators [15] as possible candidates for DEMO experiments that may eventually be performed after the completion of the planned ITER experiments (see Fig. 2). Paul's computations suggest that his quasisymmetric designs have desirable transport properties, comparable to those in axisymmetric tokamaks, while enjoying the increased stability of stellarators by avoiding the need for a large toroidal current [16,17]. Paul's many contributions in MHD were recognized by the American Physical Society's Division of Plasma Physics with his election as an APS Fellow in 2004.

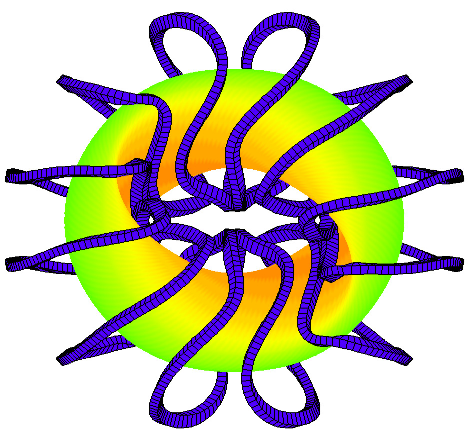

Fig. 2. A quasiaxisymmetric stellarator design with two field periods [18]. The plasma surface is shaded to indicate the magnetic field strength, and the modular coils are separated enough so that they can be constructed at reactor sizes.

Paul actively pursued his research until his death [19]. Among his many honors, Paul received the Birkhoff Prize [awarded by the American Mathematical Society (AMS) and the Society for Industrial and Applied Mathematics (SIAM)] for an outstanding contribution to "applied mathematics in the highest and broadest sense," the Theodore von Karman Prize awarded by SIAM, the National Academy of Sciences Award in Applied Mathematics and Numerical Analysis, and the Boris Pregal Award from the New York Academy of Sciences. He was a fellow of SIAM, and a member of the American Mathematical Society, the American Physical Society, the National Academy of Sciences, and the American Academy of Arts & Sciences. Although only one-quarter Armenian, he was proud of his heritage, and a hero to the Armenian mathematical community. A scientific conference in his honor will be held at the Courant Institute during the 2010–2011 academic year.

Paul's marriage to Gladys Rappaport ended in divorce. Paul is survived by his wife, Lynnel; daughters, Emily and Cathy; two grandchildren, and a sister.

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