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# Experimental Program of Heliotron J

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## Abstract

One of the objectives of the Heliotron J project is to explore the design approach of the nonsymmetric, quasi-isodynamic (omnigeneous) optimization in the heliotron line, thus leading to the establishment of the design principles for the proof-of-principle facility based on this concept. The experimental program is organized to study the high-level compatibility between good particle confinement and MHD stability as well as its divertor scheme for particle and heat exhaust at long-pulse (or steady-state) operation. The construction of Heliotron J was completed in November 1999. After the plasma breakdown test by 2.45-GHz ECH, Heliotron J achieved its first 1-T, 53.2-GHz ECH (300 kW) plasma in December. The visual indications with CCD cameras showed that the helical-axis heliotron plasma was defined clearly by the helical-axis flux surfaces as expected. The device behavior during the first experimental phase is described.

## Keywords:

Heliotron J, helical-axis heliotron, quasi-isodynamic (omnigeneous) heliotron, helical windings, heliotron improvement, bootstrap current minimization

## 1. Introduction

The design work of Heliotron J as a first step device toward the optimized helical-axis heliotron has been carried out over a 4-year period, 1995–1999, in order to carry out a new concept exploration experiment in the heliotron line. The design efforts were concentrated on the definition of its mission and the exploitation of its operational flexibility by utilizing the existing resources from Heliotron E [1,2]. The device parameters are as follows: the major plasma radius of 1.2 m, the average plasma minor radius of 0.1–0.2 m, the magnetic field strength on the magnetic axis of 1–1.5 T, the vacuum rotational transform of 0.3–0.8 with a low magnetic shear, and the magnetic well depth of 1.5% at the plasma edge, with heating systems such as 0.5-MW ECH, 1.5-MW NBI, and 2.5-MW ICRF. The design feature of this new device is, as compared with that of Heliotron E, the reduced neoclassical transport (near the tokamak level according to the DKES code) and the enhanced average beta limit (4% for the Mercier criterion) with a small bootstrap current, which carries a potential for realizing a currentless "quasi-isodynamic (omnigeneous)" optimization in the heliotron line. The validity of this concept and its ability to explore the high-quality confinement surfaces with a divertor will be fully tested in Heliotron J.

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## 2. Physics Design

The helical systems such as heliotrons with continuous helical coils and other advanced stellarators such as W7-AS or HSX with modular coils constitute complementary approaches to stellarator development and both approaches are needed to develop the physics and engineering understanding of stellarator confinement with special reference to the cost/benefit tradeoffs of the future coil design. A nonsymmetric, quasi-isodynamic (omnigeneous) optimization of the helical-axis heliotron aims at the continuous helical coil design that uses a nonsymmetric magnetic field spectrum to minimize the loss of bounce-averaged drift orbits at high beta. The quest to optimize the orbit properties has led us to investigate the favorable improvement in high-energy orbits due to finite beta. In this respect, the bumpiness of the field spectrum was found to be the key component to improve the orbit confinement [3]. Minimization of bootstrap current requires both helical and toroidal components. The role of the bumpiness as the 3rd parameter should be tested experimentally from the various aspects of its confinement characteristics. The optimal tradeoff between the simplicity of coil design, neoclassical transport, MHD and divertor by using the 3rd parameter remains as an interesting study that challenges us to develop a new concept exploration experiment in the heliotron line. In contrast to the W7-X design, it is not so easy to access this kind of optimization by using a continuous helical coil system while offering a number of new, interesting physics issues. Our present objective in the design work as well as in the experimental program is to fully develop this design approach based on the concept of a "helical-axis heliotron" and to take a first step toward the optimized helical-axis heliotron.

As a first-step design at minimum cost, a helical-axis heliotron with an aspect ratio $A = 7$ for its standard configuration was selected because it may combine attractive features of good particle confinement and edge magnetic well. The standard configuration can constitute the local isodynamic configuration in the straight confinement section of its $L = 1/M = 4$ configuration with the helical coil pitch modulation $\alpha = -0.4$ [4]. The extensive collisionless orbit calculations revealed that the prompt orbit loss rate within the vacuum core region was on the order of 20% while it could be drastically decreased down to 10% with an increase in beta (2%). It was shown that the trapped particles become confined as the localized bananas or localized superbananas. The calculations also revealed that even a weak radial plasma electric field in the level of L-mode can reduce the loss rate down to less than 10%. These significant particle confinement improvements due to beta and radial electric field are expected to introduce a special feature in the experimental confinement of Heliotron J.

## 3. Construction and Assembly

The construction of Heliotron J follows the successful experiences with Heliotron E. The key factor in its construction was a decision to use a thick vacuum vessel as the accurate guide for the $L = 1$ helical coil winding in the similar way as that of Heliotron E. The operation with nominal 0.5-s pulsed fields ($\leq 1.5$ T) should be available while the good diagnostic and heating access be maintained. The construction and assembly of Heliotron J could be divided into two main phases:

- Setting up of the support structure, the toroidal field coils (A & B), the poloidal field coils and the preparation of the two vessel halves for installation with the helical coil windings. This phase, which included the design and manufacturing of all other necessary components, and which was accompanied by a number of tests, was finished mainly in FY1998.
- The insertion of the two vessel halves with the helical coils, the toroidal coils, and the poloidal coils into the support structure, the assemblage of the main vertical coil and the upper support base, the installation of the coaxial feeders and the completion of busbar wiring and power supply rearrangement, etc. This phase began in April 1999.

Toroidal A coils are eight separate coils of 1440 mm diameter disposed in the four corner sections of the confinement configuration and each coil is composed of two sets of 10-turn, double pancakes with water-cooled, polyimide/fiber glass insulated hollow copper conductors (17 mm × 28 mm, 6 mm$\phi$). The maximum current to each conductor is 30 kA by using four parallel current circuits (120 kA for the total). Toroidal B coils are eight separate coils of 1440 mm diameter disposed in the four straight sections and each coil is composed of one set of 20-turn, double pancake with a water-cooled, polyimide/fiber glass insulated hollow cooper conductor (15 mm × 19 mm, 8.5 mm$\phi$). The maximum current to each conductor is 10.9 kA. The use of separate two toroidal coil sets can provide enough flexibility for experimentally exploring the physics effects of bumpiness in the helical-axis heliotron. Care has been taken to support the mechanical stresses due to the large electromagnetic forces resulting from the combination of toroidal and poloidal fields by using the interlocking keys between the coils.

The inner vertical coil is a set of two separate coils of 990 mm diameter disposed in the inner side of the torus to control the multi-pole field components. Each coil is composed of an 80-turn, double pancake with an air-cooled, polyimide/fiber glass insulated copper conductor (6 mm × 50 mm). The maximum current to the conductor is 6 kA. The other poloidal coils necessary for Heliotron J are the outer vertical coil (AV) and the main vertical coil (V), and these coils were complemented with the existing Heliotron-E coils.

The two vessel halves of stainless steel (SUS316) were NC machined to form the precise torus geometry with a helical trough for the helical coil winding. The highly modulated L = 1 helical coil parts were composed of 8-turn, three parallel conductors (17 mm x 28 mm, 6 mm$\phi$). The maximum current to the conductor is 40 kA with the current density of 90 A/mm$^2$ (120 kA for the total). The adiabatic temperature rise of the conductor is 57°C in the 1.2-s pulsed operation. In the four toroidal locations, the eight coaxial current feeders of the helical coil current were disposed. The error field with the toroidal mode number of 4 will be inevitable due to this arrangement, but its effect on the confinement configuration is calculated to be small.

The D-shaped cross section of the vessel was determined from the shape of the helical coil and from the requirements of diagnostics and plasma-wall studies. The minimum thickness of the wall is 20 mm. The vessel has 65 ports for pumping, diagnostics and heating. The vessel was sealed by TIG welding along two poloidal circumferences at the toroidal 90°–270° plane in compliance with high vacuum requirements. The vessel was evacuated by a set of four turbomolecular pumps, each having a pumping speed of 2400 *l*/s. As a back-up pumping system, a cryopump of a pumping speed of 10,000 *l*/s for $N_2$ gas was prepared.

The final assembly of the fabricated components was started in 1999. A very precise positioning of the coils on the device was required to obtain a good magnetic field configuration and an efficient mechanical coupling with the coil supports. As far as possible, the basic individual sub-components were extensively tested before connecting them to the device. At each stage of the assembly, the detailed measurements of positioning were made to ensure the accuracy. Figure 1 shows the photograph of the completed Heliotron J. The final commissioning of the overall system, without vacuum pumping, was made to test the system up to the coil current levels required for the first experimental phase.

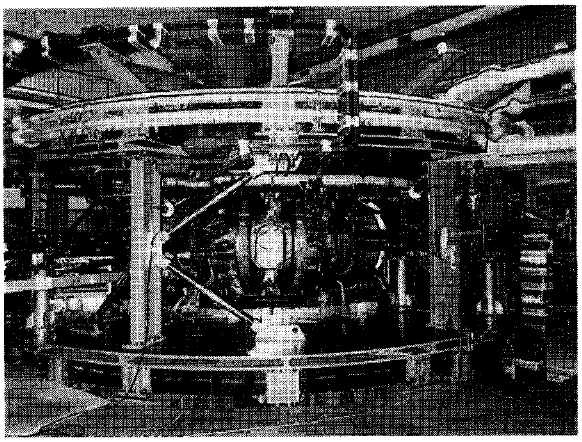


Fig. 1 Photograph of Heliotron J

## 4. Operation Tests and First Plasmas

After the construction, the operation tests of the whole system were carried out only to demonstrate the flawless performance of the device during the two months of November to December 1999. Each coil and busbar element was subjected to a thorough sequence of electrical tests. The ground insulation test was repeated after the assembly in order to verify that the coil insulation had not been damaged. The operational characteristics of the coil system such as mutual magnetic and mechanical influences, movements and elastic deformations, cooling characteristics, etc. were tested in November. Testing the coil system at levels higher than necessary was considered a risky exercise, so that a gradual increase of the parameters was preferred. Figure 2 shows an example of the coil operation tests to obtain the central magnetic field of 1 T during about 0.6 s.

After the electrical tests of the coil system, the first physics experiments were immediately carried out in December. Although the machine time of the experiment was very limited, the vacuum vessel was evacuated, leak tested, and baked up to less than 100°C for a few days. Operation tests of the plasma breakdown as well as the discharge cleaning were performed by using (i) 2.45-GHz ECH and (ii) glow discharge. Then, the first 1-T plasma shot was achieved on 8 December 1999 by using 53.2-GHz, $TE_{02}$, 300-kW ECH with an

ECH pulse length of about 10 ms. The pulse length was increased shot by shot up to 50 ms. Figure 3 shows the photograph of the 53.2-GHz ECH plasma viewed through one of the tangential ports.

In this initial operation phase, several important experiences of experimental interest were obtained:

- From the device behavior during this test phase, Heliotron J proved to work with good reliability and availability for the plasma confinement experiments.
- The visual indications with CCD cameras showed that the helical-axis heliotron plasma was defined clearly by the helical-axis flux surfaces as expected.
- The visual whisker structure at the plasma edge stimulated our interest in the experimental plan of the electron beam mapping for the edge as well as for the core region.
- A suggestion was obtained that the ECH power deposition profile could change the plasma profile by changing the position of the 2nd harmonic ECH resonance layer (0.95 T) and that the visual inspection for the magnetic-axis structure might be possible from a very narrow, snake-like plasma core.
- Runaway electrons during the ramp-up (down) phase of the helical coil current could be effectively avoided by the superposed auxiliary vertical (AV) field in the same way as that of Heliotron E.

## 5. Experimental Schedule

Table 1 shows the experimental schedule of Heliotron J to indicate the key milestones for the developmental operation:

1. The 1st milestone is to complete the installation of Heliotron J and to start the tests and commissioning of the coil system.
2. The 2nd milestone is to review the results of confinement and stability for further development of the helical-axis heliotron. The experimental program of Heliotron J is organized to clarify the direction for the helical-axis heliotron research beyond the concept-exploration level. The key issues are (i) reduced neoclassical transport, (ii) improved beta limit, (iii) compatibility between good particle confinement and MHD stability with a small bootstrap current, and (iv) exploration of the

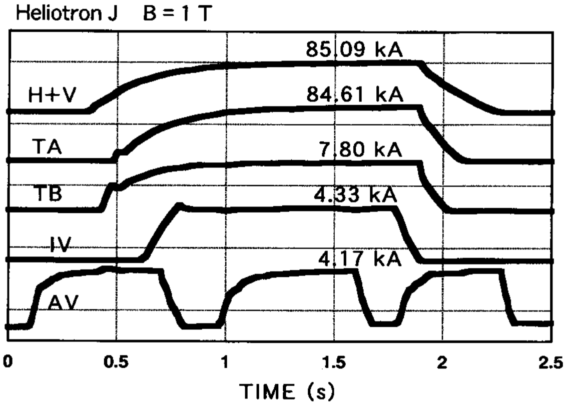


Fig. 2 Coil operation test

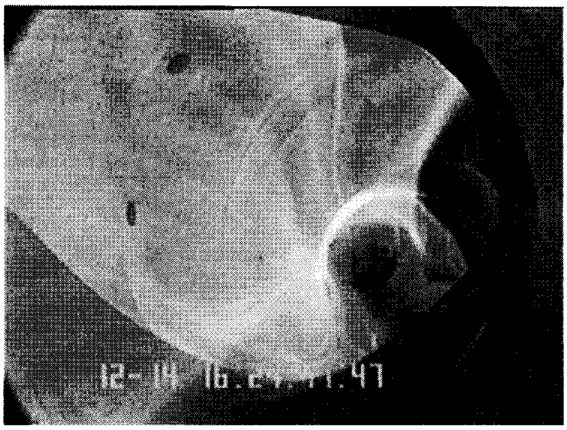
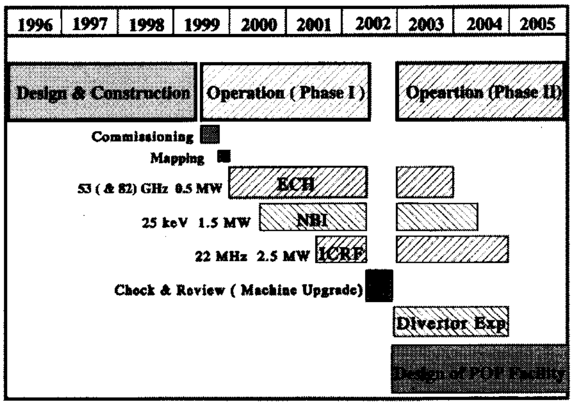


Fig. 3 Photograph of 53.2-GHz ECH plasma taken with a CCD camera through one of the tangential ports. The radiation boundary of the confined plasma is identified from the luminous separatrix layer (white stripes) as expected from the calculation [5,6].

Table 1 Experimental Program



improved confinement modes. Decision for the device modification or upgrade will depend on the results obtained in the first operation phase.

3. The 3rd milestone is to issue a final design proposal for the next device (the proof-of-principle facility) with a divertor scheme developed in the second operation phase.

Now the 1st milestone has been achieved successfully. Next, if the 2nd milestone is reached in near future, Heliotron J will provide a good chance for extending heliotron plasma parameters to a new regime and clarifying the keys to improve the stellarator confinement. Then, as the 3rd milestone, the helical-axis heliotron could offer an attractive and unique option of a fusion reactor whose configuration properties are well under external control for steady-state operation.

## References

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