NIFS--190
JP9304358

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O. Motojima, M. Hashiba, I. Fujita, T. Hino, T. Yamashina,
T. Matsuda, T. Sogabe, T. Matsumoto, K. Kuroda, S. Yamazaki,
H. Ise, J. Adachi and T. Suzuki

(Received – Sep. 10, 1992)

NIFS-190 Oct. 1992

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N. Noda[1], Y. Kubota[1], A. Sagara[1], N. Ohyabu[1], K. Akaishi[1], Hantao. Ji[1], O. Motojima[1], M. Hashiba[2], I. Fujita[2], T. Hino[2], T. Yamashina[2], T. Matsuda[3], T. Sogabe[3], T. Matsumoto[3], K. Kuroda[3], S. Yamazaki[4], H. Ise[4], J. Adachi[4], T. Suzuki[4]

[1] *National Institute for Fusion Science, Furo-cho, Chikusa-ku, Nagoya 464-01, Japan*
[2] *Department of Nuclear Engineering, Hokkaido University, Sapporo 060, Japan*
[3] *Toyo Tanso Co. Ltd., Ohnohara Plant, Ohnohara-cho, Mitoyo-gun 769-16, Japan*
[4] *Kawasaki Heavy Industries Ltd., 2-4-25, Minami-suna, Koto-ku,Tokyo 136, Japan*

A contributed paper in 17th Symposium on Fusion Technology, held in Rome, September 14 - 18, 1992, and to be published in "Fusion Technology".

Abstract

A conceptual design has been completed for the divertor plates of the Large Helical Device (LHD, R=3.9 m, a_p=50 ~ 60 cm, B_h=3 ~ 4T / superconducting coils of NbTi) and the detailed technical design is now in progress. The design concept and the status of research and development (R&D) programs are described.

[Key Words : LHD, helical divertor, divertor plate, graphite, C-C composite, OFHC, brazing, active cooling, R&D, ACT]

1. INTRODUCTION

The Large Helical Device (LHD) has been designed as a heliotron/torsatron type fusion plasma experimental device with toroidal and poloidal pitch numbers of m=10, l=2, respectively (ref.1-6). The major and minor radii of the plasma are 3.9 m and 0.5 - 0.6 m, respectively. The magnetic field strength is 3 - 4 T on the plasma axis. A pair of the helical coils and three pairs of the poloidal coils are all superconducting magnets made of NbTi.

The objectives of the LHD project are to achieve high temperature, high beta plasmas with good confinement, to investigate energy and particle transport of such plasmas, and to obtain the basic data necessary for steady state operations. For these purposes, a divertor configuration is required for the LHD device (ref. 1-2). A heliotron/torsatron configuration has an intrinsic magnetic limiter configuration. In LHD, this property is utilized to accomodate a closed divertor configuration (ref. 2,5). In order to achieve good performances of the divertor, the divertor region is disigned to be separated from main chamber surrounding the core plasma region by baffle plates. In order to achieve sufficiently low recycling of hydrogen isotopes, pumping in the divertor chamber is also under consideration. The magnetic configuration, the conceptual design of the divertor chamber and the divertor pumping are discussed in ref. 5.

In this paper, a conceptual design of the divertor plates is described. At the initial stage of the experiment, carbon based materials are the primary candidate for the plasma-facing part (armor) of the divertor plates. The status of the research and development (R&D) for C-Cu brazing unit samples is also described.

2. CONCEPT OF DIVERTOR PLATES

Figure 1 shows a schematic view of the vacuum vessel cross section, the closed magnetic surfaces and the divertor legs at two different toroidal angles of the torus. The magnetic configuration is topologically similar to double-null configurations in tokamaks, namely, both have two X points and four divertor legs running toroidally. All the legs and the X points are not lying in a flat plane, but running helically along the helical coils, which is quite different from tokamaks. Due to this complexity, it is not easy to design the divertor plate with a continuous-plate structure. On the other hand, in the LHD magnetic configuration, the poloidal magnetic field B_p is larger than toroidal field B_t arround the striking point (ref.5), meaning that the direction of the heat flow is also poloidal there, which is not the case in tokamaks. Thus, in the LHD configuration, it is easy to avoid heat concentration to the edge of carbon tiles due to misalignment, which is one of the severe problems in large tokamaks (ref.7). From above two reasons, the divertor plate is designed to be a helically running discrete-bar array, not as a continuous plate.

A schematic view of the divertor unit and the arrangement of the divertor bar array is shown in Fig. 2. Each unit of the divertor is designed as a straight, cylindrical bar, in which several pieces of cylindrical carbon armor is directly brazed to a copper cooling tube. The typical size of the unit is 30 - 40 mm in diameter and 300 - 400 mm in length. The armor thickness is 10 mm and the inner diameter of the cooling tube is 8 - 10 mm. The divertor units are attached to the headers made of stainless steel as is shown in Fig. 2 b). The gap between the two neighboring units is 3 - 8 mm, which must be adjusted to prevent the plasma stream passing through the gap and reaching the inner surface of the vacuum vessel. As is seen in Fig. 1, there are four divertor legs and each has a helical line of striking point with ~40 m in length. Then approximately 3000 units are necessary in total. The incident angle of the magnetic lines of force to the surface can be designed to be larger than 60 degree for all of the divertor units.

As is mentioned in Sec. 1, one of the aims of the LHD project is to sustain a high temperature plasma in a steady state, *i.e.*, more than 1 hour with a heating power of as high as 3 MW. For this purpose, the divertor plates must be actively cooled. Moreover, it is also required to maintain plasma discharges for 10 seconds with a heating power of 20MW. The maximum heat load on the divertor plate is estimated to be 5 MW/m^2 for the 20MW/10s operation. A total heating power of more than 30 MW is planned to apply in the later phase of the experiment, which results in the heat load of around 10 MW/m^2 for 5 sec. The requirement of the heat load is summarized in Table. 1. On the other hand, the surface temperature of the carbon armor needs to be kept below 1200 °C in order to avoid enhanced sputtering by the so called radiation enhanced sublimation (ref.8). From these requirements, direct brazing of the carbon armor to the copper cooling tube is adopted for the divertor units.

Both isotropic graphite (IG) and high thermal conductive carbon-carbon composite (CC) are considered as candidates of the armor. Oxygen free high-conductivity copper (OFHC) is adopted as the primary candidate of the cooling tube. A preliminary result of a two-dimensional steady-state calculation shows that the surface temperature of the armor is less than 600 °C with a CC armor, less than 1200 °C with an IG armor for surface heat load of 10MW/m^2. In this calculation, the velocity and the inlet pressure of the cooling water are assumed to be 10 m/s and 5MPa, respectively. The thermal stress in the divertor unit has also been calculated. The result shows that this is tolerable for both IG and CC armors. These results suggest both isotropic graphite and C-C composite are acceptable as the armor for the heat load expected in the LHD experiments.

3. RESEARCH AND DEVELOPMENT OF THE DIVERTOR UNIT

In order to achieve a heat removal rate as large as 5 - 10 MW/m^2, brazing between the carbon armor and copper cooling tube is necessary. Mechanical joint of these components results in insufficient heat transfer coefficient, which would make the surface temperature of the armor intolerably high level in terms of erosion. One of the key issues is to develop reliable brazed materials for the divertor plates. The development is in progress in collaboration with several companies, and high heat load tests on the brazed samples have started in the new site of the National Institute for Fusion Science (NIFS), which is being built in Toki-city located 30 km from the old site in Nagoya.

An electron beam facility named the Active Cooling Teststand (ACT) has been used for the heat load test. The main aims of the test are (1) to investigate the heat-removal capability and resultant surface temperature of the divertor unit and (2) to know the limit of the heat load and life time of the brazing for repetitive heat loads. The ACT device consists of an electron beam system (JEBG-1000UB1 manufactured by JEOL Ltd.), a test bench for samples, a vacuum chamber, a vacuum pumping system and a cooling water system. The beam energy is 30 keV and maximum available power is 100 kW/dc. The beam radius is less than 10 mm and the maximum scanning area is 500mm x 500mm. The geometrical pattern of the beam can be controlled by a 64 step beam controller (ST 64 DCM / JEOL). The pressure of the cooling water is 0.4 MPa at the entrance of the irradiating chamber, and its typical operating temperature is 30 C. The maximum flow-velocity of the water in the test unit is 10 m/s. The electron beam is externally controlled automatically by utilizing a digital thermo-controller unit with a beam-current monitor as a sensor. The time sequence of the beam power is programmed with this controller system. A typical scheme of the repetitive irradiation is, to raise the beam power from zero to the aimed value in 20 seconds, maintain this power level for 20 seconds, and then cut off the beam power in 20 seconds. Thus the irradiation test can be done without an operator with a repetition rate of 1 shot /minute, which enables more than 1000 irradiation tests in a day.

The test samples have been supplied from several companies. Three types of the geometry have been considered for the heat-load test, which are illustrated in Fig. 3. The first is the so called "Flat-Plate Type (F-type)", which has the simplest geometry but probably the severest in terms of residual stress after brazing. The last is the "Monoblock Type (M-type)", in which the carbon armor surrounds the copper tube without any brake. Concentration of the thermal stress is much lower than that in F-type sample, but the manufacturing process for this type is not as easy as that for F-type. The second type is intermediate between F-type and M-type, and called as the "Saddle Type (S-type)". Two types of brazing method have been proposed, namely (a) direct-brazing between the carbon and copper materials (DB), and (b) gradient functional brazing (GF), in which some interface materials are inserted between the carbon and copper materials in order to relax the residual stress.

Irradiation tests have started for GF samples fabricated at Toyo Tanso Co. Ltd. and for DB samples at Kawasaki Heavy Industries Ltd. Some preliminary results for the GF samples are presented here. The brazing method for these samples is based on a technique called as "dissolution and deposit of base metal", which is based on the mechanism of forming columnar

Fe-Cu-C alloy on the carbon surface (ref. 9). The precise brazing process is described in ref. 10.

The surface temperature of the armor is shown in Fig. 4 for two extreme cases, that is, for a M-type sample with IG armor (M/IG) and for a F-type sample with CC armor (F/CC). Isotropic graphite of IG-430U and C-C composite of CX-2002U were used for these samples. Among three pieces of the armor tile in Fig. 3, only the central one was irradiated by electron beam. The flow velocity of the cooling water was 2 m/s in this test. The heat load is 4MW/m^2 for M/IG-type, and 10MW/m^2 for F/CC-type. The surface temperature was determined with a pyrometer, where the emissivity was assumed to be 0.9. The thermal conductivity is 140 W/mK for IG430U and 390W/mK for CX-2002U at room temperature. It is clearly seen in the figure that the surface temperature of the F/CC sample is around 1200 °C and close to equilibrium in 10 seconds after the beam on even though the flow velocity of the water is as small as 2m/s. This result is promising for the LHD experiments. On the other hand, the temperature increases slowly after the beam on for the M/IG sample. Surface temperature reaches 1500 °C with a heat load as low as 4 MW/m^2. This is partly because of relatively low thermal conductivity in the armor compared with the F/CC sample and also because of the monoblock type of geometry, in which two-dimensional heat diffusion inside the armor causes slower heat transfer to the cooling tube. The surface temperature of this sample is also below 1200 °C at 10 seconds after the beam on, showing that this type is also acceptable for the LHD experiments, especially for a heat load less than 5 MW/m^2.

A repetitive irradiation test has been conducted only for the F/CC sample so far. Up to 2500 shots of irradiation with 10 MW/m^2, no serious damage nor deterioration has been found in the brazing part of this sample. The flow velocity of the cooling water was 7 m/s for this experiment.

Although the results are still preliminary, these are all promising for the LHD application. More systematic tests are in progress for various types of samples. The first goal of the experiment is to find out several combinations between the armor materials, geometrical types and brazing methods which satisfy the LHD requirement. The limiting heat load will be also investigated for these samples in terms of heat removal and brazing reliability.

4. SUMMARY

(1) The divertor plate of the LHD device is designed to be a helically running discrete-bar array. The unit of the plate has a cylindrical carbon armor directly brazed to a copper cooling channel. The units are attached to a header made of stainless steel and actively cooled by pressurized water in order to keep the surface temperature below 1200 °C for a heat load of 5 - 10 MW/ m^2 expected in the LHD experiments. Approximately 3000 divertor units are necessary for covering all four divertor legs.

(2) Both isotropic graphite and carbon-carbon composites are candidates for the armor material of the divertor unit. Brazing technique of these materials to OFHC are under development in collaboration with several companies. Two types of brazing method have been successfully applied, namely, direct bonding between carbon and copper, and gradient functional bonding in which interface materials are inserted in the bonding section.

(3) The heat load tests for various types of the divertor unit sample have started using an electron beam facility named ACT. The surface temperature of a F/CC type samplewas around 1200 °C for 10 MW/m^2 in a steady state, which satisfies the heat load requirement of the LHD divertor. The surface temperature for an M/IG type sample was not in an equilibriumat 10 seconds after the beam on, but below 1200 °C for 4 MW/m^2. This type is possible to be applied for a heat-load condition less than 5 MW/m^2. After 2500 shots of irradiation with 10 MW/m^2, no serious damage nor deterioration has been found for the bonding region of a F/CC sample. Although these results are still preliminary, they are promising for application of the brazing materials to the LHD divertor plates.

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Table 1. Heat load condition in LHD

total heating power (MW)	heat load (MW/m^2)	duration (sec.)
3	0.75	steady
20	5	10
>30	10	5

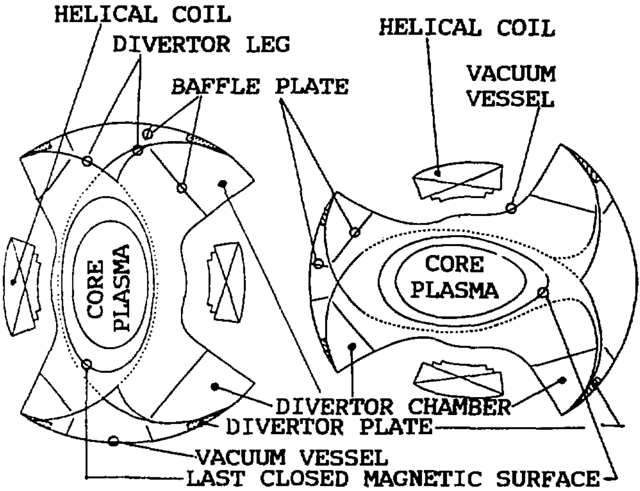

Fig. 1 Cross sectional view of the LHD device
Torus axis is on the left hand side.

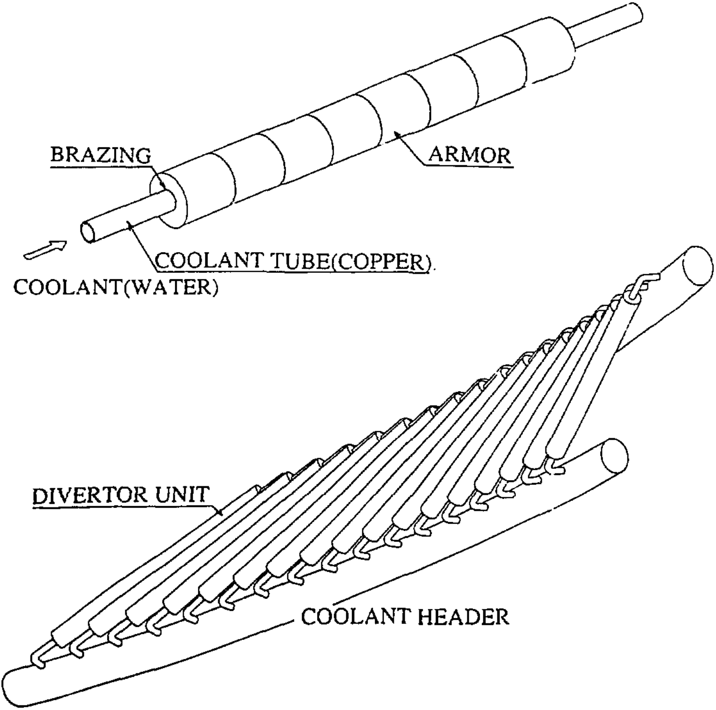

Fig. 2 Concept of the divertor plate
Top: divertor unit Bottom: divertor block

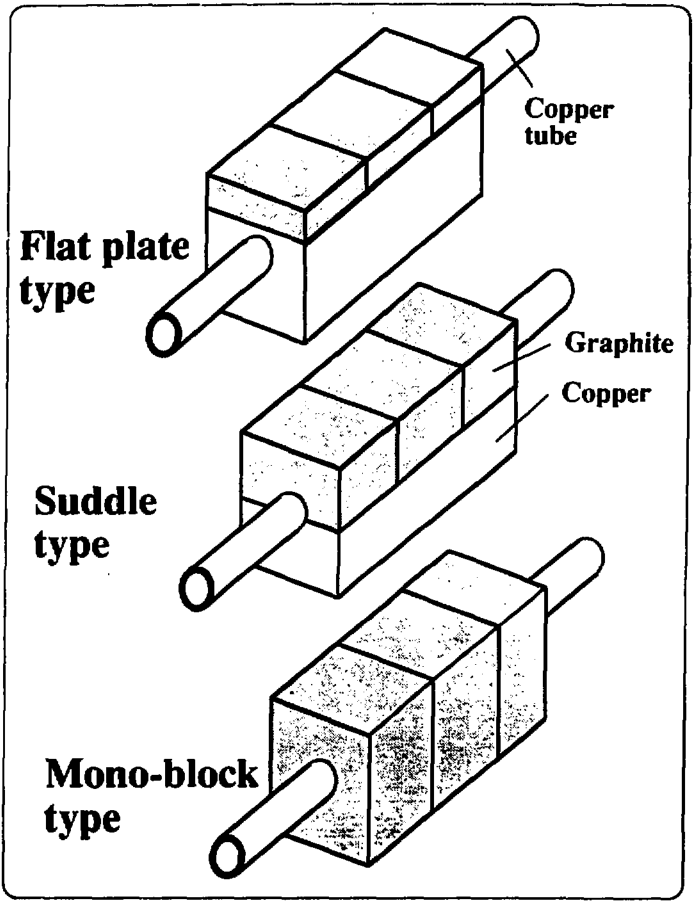

Fig. 3 Test samples of the divertor unit

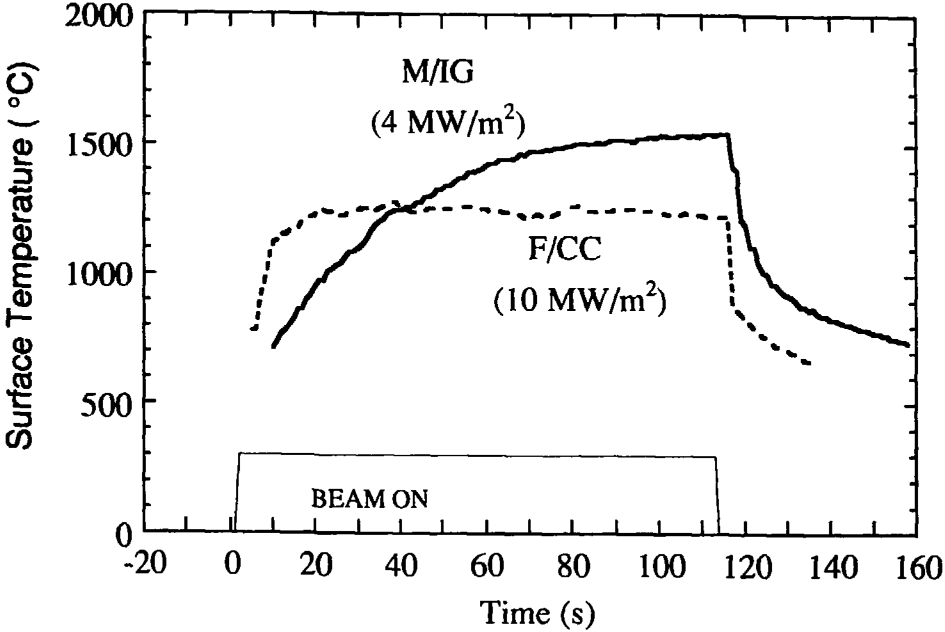

Fig. 4 Surface temperature obtained in irradiation test with the electron beam facility ACT (Active Cooling Teststand)

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