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Strain Monitoring System for Cryogenic Structure of Large Helical Device

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Abstract

The Large Helical Device has the world's largest class cryogenic structure to support huge electro-magnetic force generated by superconducting coils. The strain monitoring system was designed and installed in the Large Helical Device to evaluate the soundness of the large cryogenic structure and the measurement has been done continuously during the operation. Some experimental results are presented in the paper and the strain behavior is discussed. No significant difference of the strain has been observed up to now. The fact gives a conclusion that the cryogenic structure is working on well without any faults. By piling up the data sets, the understanding for the cryogenic structure will get ahead and the certainty and reliability for the fault or damage will be enhanced.

Keywords:

Large Helical Device, cryogenic structure, strain measurement, superconducting coil, electro-magnetic force

1. Introduction

A large superconducting coil system was constructed for the Large Helical Device (LHD) to generate a strong magnetic field of up to 3 T at plasma axis [1]. To support the superconducitng coils and the huge electro-magnetic force, a cryogenic structure was designed and constructed [2]. The austenitic stainless steel (SUS316) was used as the structural material and the maximum thickness was 100 mm [3]. The support structure is cooled down to 4 K together with superconducting coils at each campaign and endures the electro-magnetic force during coil excitation. The plasma experiments have been conducted successfully [4] and the fifth campaign began on September, 2001 and is going on now.

The LHD is the first machine of which coils are all superconducting and will be operated for a long time. So, a strain measurement and monitoring system was considered and installed in the LHD to measure the stresses and strains and to evaluate the condition of the structure under electro-magnetic force at 4 K. The strain monitoring was carried out under the same operation mode and the soundness of the structure was evaluated comparing with the data obtained before. Since such a strain monitoring system was not developed before in the large plasma experimental devices, it is very important to develop the monitoring system and investigate the status of the support structure from the points of device engineering and maintenance engineering views for a fusion machine.

In this paper, an outline of the strain monitoring system is described and some data are presented. The data shows that the cryogenic support structure in the LHD is working on well without any problems.

2. Outline of Strain Measurement

For an application to the LHD strain monitoring

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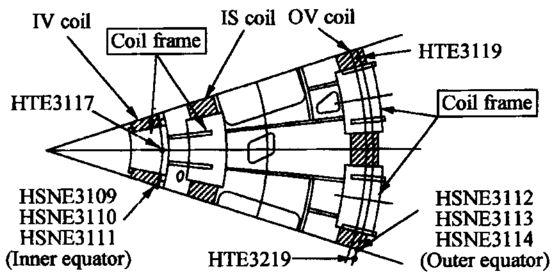
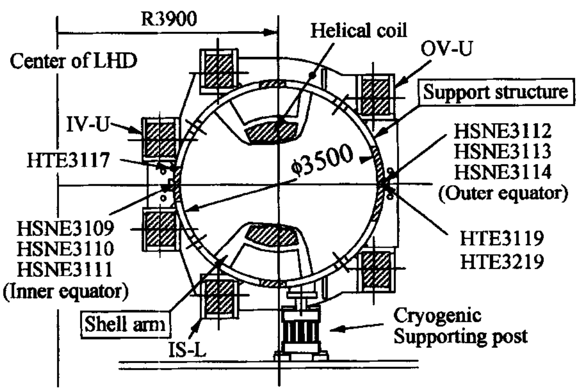
system, a new strain gage was developed to have small apparent strain at 4 K and had polyimid coated gage lead wires which allowed fine-twist of the wires [5,6]. The gage has a base diameter of 20 mm, a gage length of 5 mm, an electric resistance of 350 Ω and a gage factor of about 2.0.

A Wheatstone bridge was formed near an active gage using three dummy gages to reduce the temperature effect on the apparent strain and to cancel the apparent strain induced by the fluctuating magnetic field. The dummy gages were attached on a so-called dummy stage, which was a 3 mm thick stainless steel plate clad with copper, welded near the active gage. An adhesive of a polyurethane system was used for the active gage, because the agent solidified at room temperature and it was hard to heat up the support structure. For the dummy gage, a phenol system was applied and the stage was heat- treated at 353–423 K to solidify the agent. A cable connecting the Wheatstone bridge to a feed through connector was also newly designed and fabricated taking account of reduction of the electric or magnetic noise and heat load to the



(a) Top view of Sector 1.



(b) Cross sectional view of Sector 1.

Fig. 1 Cryogenic structure of LHD and location of strain gages.

cryogenic structure. Two pairs of twisted wires were again twisted, and the cable was electrically shielded and finally covered with a fluoroethylene polymer. One twisted pair was used for a constant input current and the other was for an output voltage.

The LHD has a cryogenic support structure which sustains one pair of helical coils and three pairs of poloidal coils. All coils are superconducting and cooled down to 4 K together with the support structure. The structure consists of ten sectors and one sector covers 36 degrees at center angle. The top and the cross sectional views of Sector 1 are shown in Fig. 1. On the top view, inner vertical (IV), inner shaping (IS) and outer vertical (OV) coils are located and fixed to the support structure (shell structure) with coil frames. On this cross section, helical coils are running at the top and the bottom sides. The helical coils are set in the coil can and welded to the support structure with two shell arms. On the assemble process, each sector was welded in upper half and lower half independently and then both halves were welded at the inner and outer equators. Therefore, there are cross joints of welding at the cross point of the equators and toroidal cross section of the sector. The strain gages were attached on the cross point of the welding passes [7].

Tri-axial strain gages (three gages were set in one base) were used, and three tag names were prepared for one strain gage base as shown in Fig. 1. HSNE3109 and 3112 show the strains in the toroidal direction, HSNE3111and 3114 indicate those in the poloidal direction, and HSNE3110 and 3113 are those in 45 degree direction to the torus. HTE3117 and 3219 are thermo- sensors (Cernox) located under IV-U coil frame and on the outer equator. In the case of Sector 2, the second number from left side in the tag becomes 2. For example, HSNE3111 and HSNE3114 change to HSNE3211 and HSNE3214 in Sector 2.

Since the helical coils are pool boiling type superconducting coils, the coil can is filled with liquid helium and the temperature is kept at the boiling temperature of the helium. The poloidal coils are forced flow type superconducting coils. So, supercritical helium is forced to flow into the conduit of the coil. The inlet temperature is controlled at 4.5 K under the gage pressure of 0.9 MPa. The cryogenic support structure is cooled by two-phase helium at around 4.5 K using 40 parallel cooling channels. Depending on the quality of the two-phase helium, the inlet temperature changes slightly during the cooling.

3. Results and Discussion

The LHD plasma experiment program has several operation modes to create different magnetic surface. In this paper, the results obtained under #1-d mode with gamma of 1.258 will be presented. Naturally, the strain condition of the structure depends on the electro-magnetic force generated by the superconducting coils. So, the operation mode was fixed to compare the data sets easily.

The helical coil has 450 turns of superconductors which were divided into three parts, i.e., inner part, middle part and outer part designated as H-I, H-M and H-O, respectively. The inner part is the nearest to the plasma. The current of each part can be operated independently. Under #1-d mode, a radius of the magnetic axis is 3.6 m and the currents of each part of the helical coil are 10.749, 11.628 and 11.823 kA for H-I, H-M and H-O respectively at 2.85 T at the plasma axis. It results in gamma of 1.258. This current distribution gives the current center outward shift in the miner radius direction.

The LHD has no electrical break in the torus. So, an eddy current runs around and heats up the structure when the magnetic field increases or decreases so quickly. This temperature rise makes the strain measurement difficult, because the additional apparent strain appears. Therefore, the lower ramp rate of 0.02 T/min was adopted.

Figure 2 shows one example of the slower ramp-up and ramp-down operation conducted on November 29, 2001. The operation mode was #1-d with γ of 1.258 as explained above. The temperatures near the inner equator and on the outer equator vary within about 0.02 K. The temperature change on the inner equator becomes larger than that on the outer equator as reported before [5], and this fluctuation is considered to be caused by the change of the quality of the flowing helium.

Such slow ramp rate operations were carried out three times to measure the strains under coil excitation. The first was carried out on October 4, 2000 at the beginning of the forth campaign, and the second was done on January 19, 2001 at the ending of the campaign. The last was performed on November 29, 2001 during the fifth campaign.

The examples of the measured strains are shown in Fig. 3. In the figure, the results of HSNE3111 and 3114 are described and those are plotted against the square of the magnetic field at the plasma axis which is corresponding to the electro-magnetic force. Therefore, the relation becomes straight line when the structure responds to the electro-magnetic force elastically. The strains on the inner equator are smaller than those on the outer equator, for the outer vertical coils generate huge tensile electro-magnetic force to make an inward shift of the plasma axis.

The results of HSNE3111 shows a hysteresis curve and this would be caused by the different deformation process of the helical superconductors on the ramp-up and ramp-down processes [7]. On the other hand, HSNE3114 presents linear relationship. These tendencies are observed both on October 4, 2000, January 19, 2001 and November 29, 2001.

To investigate the difference and the scatter of these hysteresis curves, the measured strains were compared at the same magnetic field. The results are

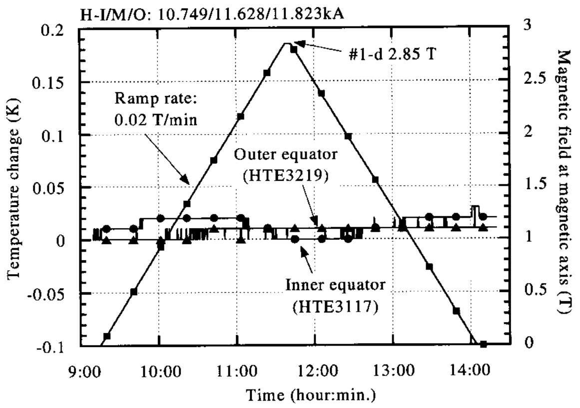


Fig. 2 Change in temperature and magnetic field under #1-d mode with γ of 1.258 measured on November 29, 2001.

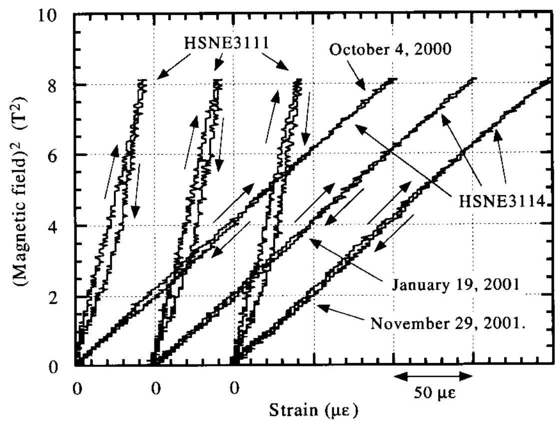
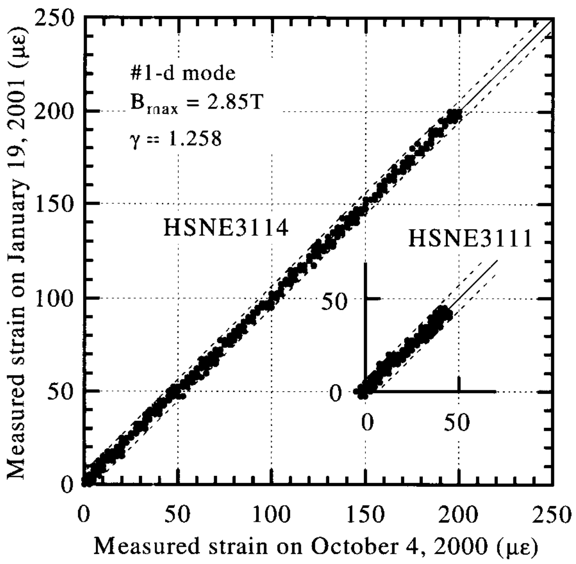


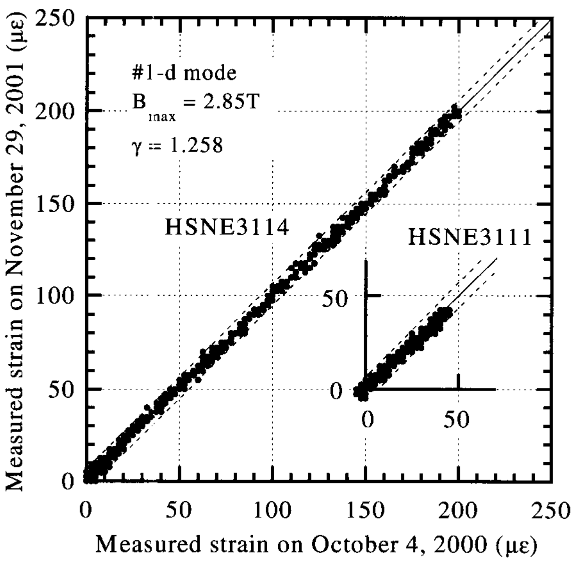
Fig. 3 Comparison of hysteresis curves between square of magnetic field and measured strain.

shown in Fig. 4. Figure 4 (a) indicates the results of January 19, 2001 against October 4, 2000 and (b) is the results of November 29, 2001 against October 4, 2000.

The data acquisition system has an error of +/– one digit fundamentally. So, the error of +/– two digits is involved in the results shown in Fig. 4. In addition, another error of +/– one digit will be generated when the data are compared each other at the same magnetic field.



(a) Comparison of strains measured on October 4, 2000 and January 19, 2001.



(b) Comparison of strains measured on October 4, 2000 and November 29, 2001.

Fig. 4 Comparison of scatter of data set.

In both figures, the total error will become +/– three digits. Therefore, +/– three digits boundaries, which correspond to about +/– 7.5 με, are displayed by the dotted lines. It is very clear that all the experimental points of HSNE3111 and 3114 on January 19, 2001 and November 29, 2001 are plotted within the +/– three digits scatter bands.

From these results, it can be concluded that the cryogenic support structure is not damaged at all after the plasma experiments in the forth campaign and the warming up and cooling down processes before the fifth campaign.

The change in the measured strain on each sector is summarized in Fig. 5. The number in the horizontal axis indicates the sector number and measured strains of HSNE3X11 and 3X14 are plotted in the corresponding box, where X is Sector number. Round, triangle and square symbols show the result of each monitoring on October 4, 2000, January 19, 2001 and November 29, 2001. Depending on the sector, the measured strain changes very much, for the horizontal port shape and dimensions are not the same. In addition, the location of the strain gage is not entirely in the symmetric position. However, when each three data sets are compared, the difference is within three digits, and mostly two digits. Taking account the error of two digits into consideration, it is possible to make a conclusion that the strain does not change and that the cryogenic structure is not damaged at all up to now.

These results described above reveal that the strain measurement system installed in the LHD is very effective to evaluate the status of the cryogenic support structure during the coil excitation. The continuous data

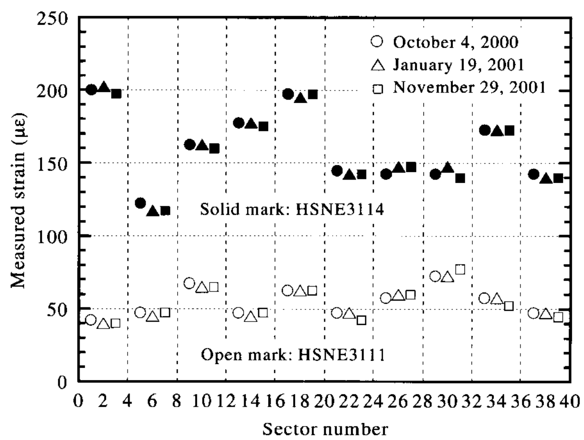


Fig. 5 Measured strains at 2.85 T under #1-d (γ = 1.258) during the forth and the fifth campaign.

acquisition and piling up the data will enhance the certainty of the monitoring system and the reliability of the evaluation of the cryogenic support structure. It is expected that the system will give a special warning on a certain fault of the structure before the trouble occurs.

4. Summary

The LHD has the large cryogenic support structure which sustains one pair of helical coils and three pairs of poloidal coils. To measure the strain during coil excitation and to evaluate the soundness of the structure, the strain monitoring system has been considered and installed in the LHD as part of the fusion device engineering. During the consideration, new gages and wires were designed and developed. The strain measurement has been performed continuously and the investigation on the structure has been carried out under a certain operation mode specially selected for this purpose.

In this paper, the outline of the strain monitoring system is described and some results are presented. The main results are summarized as follows:

(1) The slower ramp rate operation condition, (#1-d mode, $\gamma = 1.258$, maximum magnetic field; 2.85T) gives a clear data set of the strain monitoring for the cryogenic structure.

(2) The hysteresis curve between the square of the magnetic field and the strain does not change on October 4, 2000, January 19, 2001 and November 29, 2001.

(3) The total strain under the change of the magnetic field from zero to 2.85 T shows no significant difference among three monitored data sets.

(4) From these results, it should be concluded that the cryogenic support structure in the LHD works well without any problems up to now.

(5) The strain monitoring system is working effectively and expected to give a warning before unexpected trouble.

(6) The continuous data acquisition will make the certainty and reliability of the system higher and the system work more effectively.

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