Electromagnetic Fields Measurement and Safety Consideration in Magnetic Confinement Fusion Test Facilities*)

Tatsuhiko UDA, Masahiro TANAKA, Shizuhiko DEJI[1)], Jianqing WANG[2)] and Osamu FUJIWARA[2)]

National Institute for Fusion Science, 322-6 Oroshi, Toki 509-5292, Japan
[1)]*Gifu University of Medical Science, Hiraganagamine, Seki 501-3892, Japan*
[2)]*Nagoya Institute of Technology, Gokiso, Showa-ku, Nagoya 466-8555, Japan*

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The environmental electromagnetic fields were measured around a magnetic confinement fusion test facility namely Large Helical Device (LHD) which is equipped with large superconducting magnet coils system and high-power plasma heating systems of Neutral Beam Injection, Electron Cyclotron resonance Heating and Ion Cyclotron Range of Frequencies (ICRF) heating. The leakage of the static magnetic field from the LHD was less than 1.2 mT, and it varied according to the coil operation. The extremely low frequency electromagnetic field was measured around power supply units for the coil system, and the magnetic field of higher than the guideline level of the International Commission on Nonionizing Radiation Protection (ICNIRP) was predicted. Leakage of high frequency electromagnetic field from the ICRF was observed in bursts according to plasma shots. The measured values were less than the occupational guideline levels. Although the electromagnetic fields were less than the regulation levels, more monitoring survey is necessary from the view point of occupational safety.

Keywords: magnetic confinement fusion facility, LHD, static magnetic field, ICRF, electromagnetic fields, safety

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1. Introduction

Experiments using the magnetic confinement nuclear fusion devices had been made remarkable progress over the last decades. To realize the nuclear fusion reactor, it has to control and confine high temperature, high density plasma in a torus shape vessel by strong magnetic fields. In recent years, many types of fusion test device using the superconducting magnet system are operated or being constructed, for example LHD [1], JT-60SA [2], KSTAR [3] and EAST [4] etc. To obtain the high temperature plasma, it is usually realized by three types of auxiliary heating systems: Neutral Beam Injection (NBI) system, Electron Cyclotron resonance Heating (ECH) system and Ion Cyclotron Range of Frequencies (ICRF) heating system. In the presence of a uniform magnetic field, it is known that a charged particle undergoes a cyclotron gyration with a characteristic cyclotron frequency. In order to heat the plasma, resonance heating methods are applied for a magnetic confinement fusion experiments. In a fusion test facility, therefore, safety issues arise to protect from not only ionizing radiation but also non-ionizing radiation such as the leakage of static magnetic field and radio frequency (RF) electromagnetic fields. The frequency range of the electromagnetic fields is very wide from Extremely Low Frequency (ELF: few tens Hz) to very high frequency (ex. 168 GHz) [5, 6]. In addition, a distinctive feature of magnetic confinement fusion test facilities is the presence of electromagnetic pulses and stochastic varying fields [7, 8]. As for the static magnetic field, Kubota *et al.* attempted dosimetric measurement of the static magnetic fields around a satellite device of a linear plasma simulator [9]. The LHD, which is a stellarator/heliotron type of fusion test device, has the largest superconducting helical and poloidal coils system in the world [1]. The specification of the LHD is summarized in Table 1. Since 1998, several-month-long operation campaigns have been conducted in annual. The superconducting coils have been excited more than 1400 times, and more than 11000 plasma discharges have been produced. Figure 1 shows layout of the LHD, plasma heating electric devices and the measurement probe set points in the LHD building. Except for the superconducting magnet coils system, the major electric devices are the coil power supply and motor genera-

Table 1 Specification of the LHD.

Major radius	3.9 m	
Minor radius of helical coil	0.975 m	
Minor radius of plasma	0.5 to 0.65 m	
Magnetic field	3 T at R = 3.9 m	(2.96 T at R = 3.6 m)
Magnetic energy	0.9 GJ	(0 .77 GJ)
Heating power		
ECRH 77-168 GHz	10 MW	(2.5 MW)
ICRF 25-100 MHz	3 MW	(3 .0 MW)
NBI	15 MW	(23 MW)
Steady state (ICRF+ECRH)	3 MW	(1 .7 MW)

*Values achieved are shown in parentheses

author's e-mail: Uda.tatsuhiko@nifs.ac.jp

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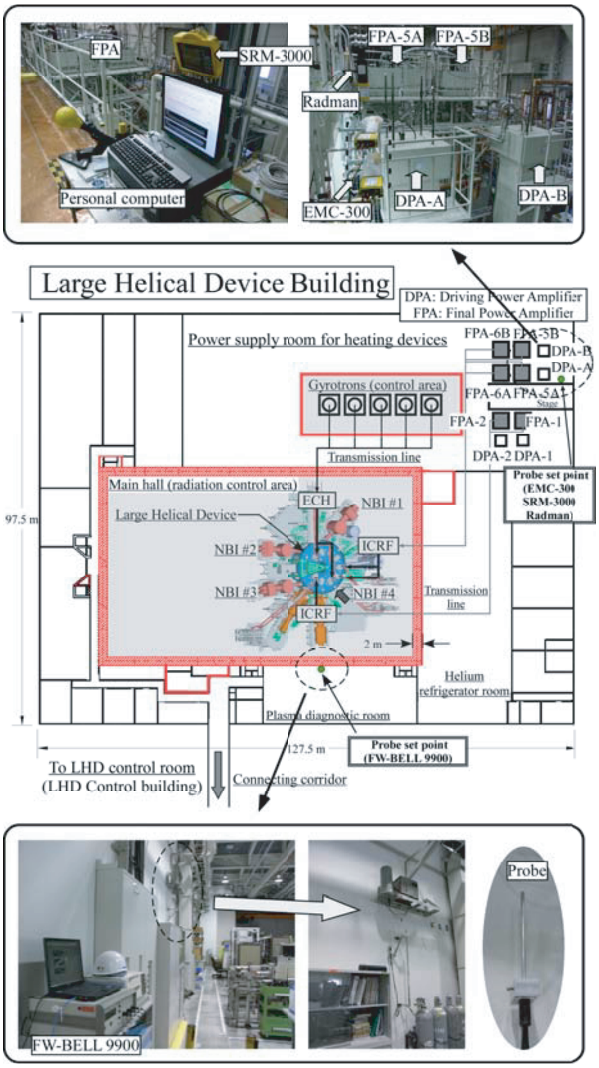

Fig. 1 The layout of the LHD and plasma heating electric devices, and measurement probe set points.

tor, which comprises the power supply to the neutral beam injection of ELF, a microwave generator of 2.45 GHz for discharge cleaning of first wall and plasma facing components, plasma heating devices such as the MHz level ion cyclotron range of frequency, and the GHz level electron cyclotron resonance heating. Although the structural materials of the LHD and related devices absorb high-frequency electromagnetic waves, leakage of various frequencies of electromagnetic fields is a safety concern. Considering the occupational safety, we measured the electromagnetic fields around the LHD and heating devices. The results of preliminary test of monitoring instruments and safety consideration for electromagnetic fields had been reported [5, 6, 10, 11]. A previous study of safety guidelines applying to the NIFS referred to the recommendations and guidelines of the World Health Organization (WHO) and the ICNIRP [12–15]. The objectives of this study introduce the measurement results on leakage electromagnetic field with various frequencies in a magnetic confinement fusion test facility.

2. Experimental System

2.1 Layout of instruments

The layout of the LHD is illustrated in Fig. 1, showing the locations of the high frequency generating devices for plasma heating and the measurement instruments. The area shaded gray is a radiation-control zone and is regulated to keep out during discharge operation of the LHD. The power supplies for magnetic coils and the NBI is located at another floor. In the LHD building, there are two types of high frequency generating devices. The first is a gyrotron which generates high frequency electromagnetic waves at 77, 84, and 168 GHz for the ECH. The second is an oscillator that generates frequencies in the range of several tens of MHz for ICRF heating. In this paper, we focused on monitoring only the region around the amplifiers for the ICRF oscillator. The probes for high frequency electromagnetic field measurement were set up near the stage toward the final power amplifier (FPA-5A, 5B) and the driving power amplifier (DPA-A, B). The distance between the probe and amplifiers is several meters as presented in Fig. 1 and in the photograph. In addition, leakage of the static magnetic field from the LHD was measured from outside of the 2-m-thick concrete wall, which serves as a radiation shield, at a location 23 m far from center of the LHD. The measurement height was 3 m lower than the horizontal center level of the LHD plasma. Photographs of the monitoring system are shown in Fig. 1.

2.2 Measurement instruments

The leakage of the static magnetic field and ELF, and RF electromagnetic fields were measured using commercially available probes. Specifications of the measurement instruments are summarized in Table 2 (a)-(c). The static magnetic fields were continuously measured using electrical logger system. Also the high frequency electromagnetic field near the ICRF devices were continuously measured using two kinds of isotropic radiation meters EMC-300EP and SRM-3000 (narda S.T.S.) as summarized in Table 2 (c). Considering that the ICRF heating operation lasts for a few second, the sampling rate used provides a sufficient time resolution. These probes have a sufficient bandwidth to detect the range of frequencies being emitted by the ICRF oscillator. The extremely low RF magnetic field leaked from the ICRF was detectable by SRM-3000, of which sensitivity is much higher than that of EMC-300EP.

3. Measurement Results

The plasma shot experiments of LHD are carried out from 9:00 to 18:45. A shot is usually made every three minutes and ICRF heating is also performed at the same time if required.

3.1 Static magnetic field

The leakage of magnetic field strength outside of the

Table 2 Specifications of measurement instruments for the leakage of electric and magnetic fields.

(a) Static magnetic field		
Instrument model	Gauss Meter 9900 (F.W.BELL)	
Detection device	Hall-effect device	
Probe axis	3	
Measurement frequency	DC - 50 kHz	
Measurement range	1 nT - 10 T	
Sampling interval	2 sec.	
(b) ELF magnetic field		
Instrument model	ELT-400 (narda S.T.S) connect to TDS 3034 (Tektronix)	
Detection device	Isotropic Coil 100 cm^2	
Probe axis	3	
Frequency range	Low (Low cut: 30 Hz)	
Measurement range	> 80 mT (80 mT mode)	
(c) High frequency EMF		
Instrument model	EMC-300EP (narda S.T.S.)	
Probe element	Type18 (Electric field)	Type10 (Magnetic field)
Probe axis	3	
Measurement frequency	100 kHz - 3 GHz	27 MHz - 1 GHz
Measurement range	0.2 - 320 V/m	0.025 - 16 A/m
Sampling interval	0.2 sec.	
Sensitive Instrument model	SRM-3000 (narda S.T.S.)	
Probe element	Probe 3581/01 (Magnetic field)	
Probe axis	3	
Measurement frequency	100 kHz - 250 MHz	
Measurement range	25 μA/m- 560 mA/m	

LHD hall has been continuously measured since 1998. The typical leakage magnetic strength at a fixed point, where is shown in Fig. 1, increases from the daily experimental start to shut down as shown in Fig. 2 (a). The magnetic field strength was about 2.7 T at the center of plasma. The strength varied slightly in each shot. A small peak of less than 0.01 mT was observed according to the power supply to the local island divertor (LID) coils, which control the magnetic island field at the edge plasma to improve the plasma confinement properties. Another possible cause is effect of the presence of plasma currents induced by the plasma pressure gradient, electron cyclotron waves and/or neutral beam injection heating. These values were obtained by subtracting background namely the level at a.m. 0:0, that is about 0.06 mT, then it is approximately twice of a terrestrial magnetic field. Such magnetic fields increase with magnetization of steel such as cabinets near the monitoring point. Daily maximum leakage of static magnetic strength since 1998 of the 1st cycle to the 15th cycle is shown in Fig. 3. The superconducting magnet coil system has two types of coil protection sequence providing against quenching or an abnormal event. They are named 1 M mode and 1Q mode of which magnetic force decreasing time constant is 5 min and 20 sec respectively. The static magnetic field observed was spontaneously in-

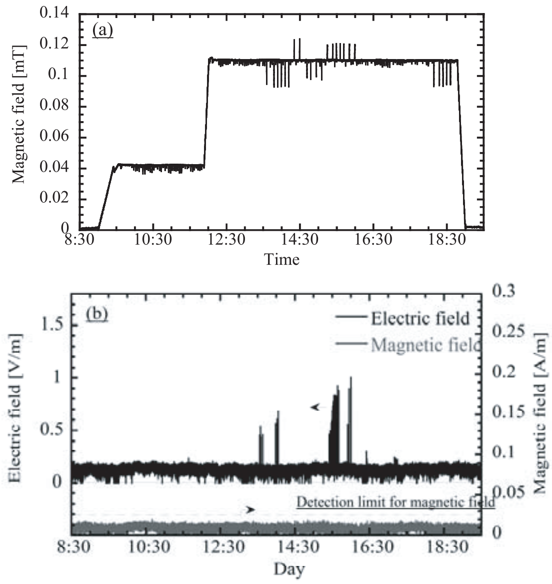

Fig. 2 Leakage of electromagnetic fields in the LHD facility, (a) static magnetic field, (b) RF electromagnetic field.

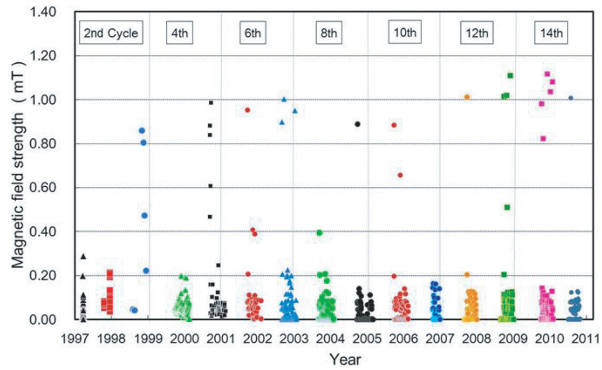

Fig. 3 Leakage of static magnetic field measured since 1st cycle in 1998. The background is subtracted.

creased to about 1.2 mT because the balance of the helical and poloidal coils might change. Although the level observed was small, from view of safety it must be considered not only absolute magnetic strength but also its rise time and gradient field.

3.2 Extremely low frequency magnetic field

The ELF magnetic field was measured near the electric power supply units for the superconductive coils. A relation of time and measured wave spectrum is shown in Fig. 4 (a). From the spectrum analysis, the maximum ELF magnetic field was observed at 120 Hz, corresponding to second harmonic wave of 60 Hz as shown in Fig. 4 (b). The third harmonic wave, 180 Hz, was also observed as maximum field, depending on the location. The peak strength observed was over 100 μT. However there are some harmonic frequencies of EFL, the actual magnetic strength would be multiple of many frequencies. As reference the occupational guide line of ELF recommended by the IC-

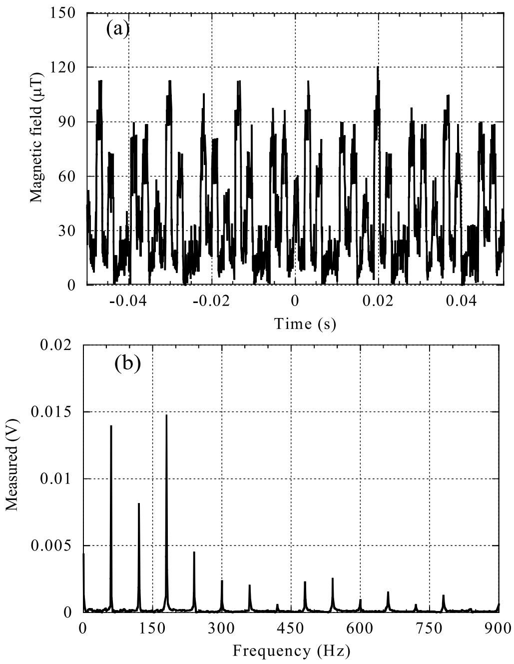

Fig. 4 ELF magnetic field measured near the LHD superconductive coils electric power supply units, (a) time spectrum, (b) frequency analysis.

NIRP is 25/f μT (f: frequency, kHz) [14]. Thus, workers need to prevent from approaching the area of the electric devices under the operation. Another major ELF field generating device is the motor generator for power supply to the NBI, as reported elsewhere [5]. Usually it was distributed in 0.2-40 μT.

3.3 High frequency electromagnetic field

Leakage of high frequency electromagnetic fields around the ICRF oscillator and amplifiers had been measured. The ICRF devices are operated in bursts, typically from one second to one hour. Among the ICRF sources room in Fig. 1, the measurement instrument was set toward the targeted driving power amplifiers (DPAs) A and B. Figure 2 (b) shows an example of electric and magnetic fields. The burst like peaks had been observed according to not only plasma heating experiments but also the tests operation of ICRF device. The maximum electric field strength observed in each shot was less than 1 V/m that is less than guideline limit of 61.4 V/m. On the other hands, the signal of leakage magnetic field could not be observed because of less than the detection limit that is around 0.025 A/m. The guideline limit is usually defined as mean of 6 minutes, then average of the short pulse time shots becomes extremely small even though they are high intensity shots. Although electric fields were detected by the EMC-300EP probe, magnetic field could not be detected. Then we applied by the SRM-3000 detector for the feasibility study. Then it was found that many burst like magnetic fields were detectable and the values were distributed around 0.1 mA/m of which level was less than the guideline limit of 0.163 A/m. Although the SRM-3000 is sensitive and it could measure spectrum, it is not suitable for continuous monitoring, because it requires heavy memory and speed for the data logging instrument. The ECH produces high frequency electromagnetic field around 100 GHz. To measure the occupational guideline level of such high frequency will be a future problem.

4. Conclusions

The environmental electromagnetic fields were measured around the LHD. Except the ELF magnetic field around the super conductive coils power system, all the observed values were less than the occupational guide line levels proposed by the ICNIRP. However, major environmental electromagnetic field in the magnetic confinement fusion test facility is generated in time-dependent mode. We would suggest considering not only steady mode but also statistically varying mode from a view point of occupational protection. Including multiple places more electromagnetic field measurements should be continued.

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