Fusion Product Diagnostics based on Commercially Available Chemical Vapor Deposition Diamond Detector in Large Helical Device

K. Ogawa[a,b,1], M. Isobe[a,b], C. Weiss[c,d], E. Griesmayer[c,d], S. Sangaroon[e], E. Takada[f], S. Masuzaki[a], H. Ohtani[a,b], L. Liao[b], S. Tamaki[g], I. Murata[g], and M. Osakabe[a,b]

[a] *National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, 509-5292, Japan*
[b] *The Graduate University for Advanced Studies, SOKENDAI, Toki, 509-5292, Japan*
[c] *CIVIDEC Instrumentation GmbH, Schottengasse 3A/1/41, 1010 Wien, Austria*
[d] *Technischen Universität Wien, Atominstitut, Stadionallee 2, 1020 Wien, Austria*
[e] *Mahasarakham University, 20 41 Kham Riang, Kantharawichai District, Maha Sarakham 44150, Thailand*
[f] *National Institute of Technology, Toyama collage, Toyama, 939-8045, Japan*
[g] *Osaka University, Suita, 565-0871, Japan*

E-mail: ogawa.kunihiro@nifs.ac.jp

ABSTRACT: Fusion product diagnostics based on four commercially available single-crystal chemical vapor deposition (s-CVD) diamond detectors are installed in the Large Helical Device (LHD) in order to understand energetic ion confinement. Characteristics of s-CVD diamonds were surveyed using alpha and D-T neutron sources. It is found that the energy resolutions of s-CVD diamonds for ~5 MeV alpha particles and 14 MeV neutrons are 1%-3% and ~1.7%, respectively. Moreover, the response of four s-CVD diamond detectors to alpha particles and D-T neutrons is almost identical. The installation positions of the diamond detectors in the vacuum vessel are searched for, based on the loss points of charged fusion products reckoned by Lorentz orbit calculations. Energy- and time-resolved measurement of fusion product flux will progress in further understanding of energetic ion confinement in LHD.

KEYWORDS: Diamond Detectors; Neutron detectors; Plasma diagnostics - charged-particle spectroscopy.

Contents

1. Introduction

Research toward fusion power generation, considered to be unlimited clean energy, has been intensively performed to solve energy problems. A phase of this research is about to enter the nuclear-burning plasma era, as represented by ITER[1]. In the upcoming fusion burning plasma research era, neutron diagnostics is regarded as one of the essential diagnostics[2, 3]. In fusion-burning plasmas, neutron energy reflects fuel ion velocity distributions. Therefore, neutron energy spectrum measurements in thermal plasma can provide the fuel ion temperature[4-6], fuel ratio[7-9], and plasma rotation[10]. Moreover, neutron diagnostics provide information on energetic ion confinement in currently functioning neutral-beam-heated or ion-cyclotron-range-of-frequency-heated plasmas[11, 12].

The diamond detectors[13] have been developed to be utilized in fusion plasma research due to their attractive potential in fusion plasma diagnostics, e.g., compactness and their potential for measurement in high-irradiation and high-temperature conditions[14]. This is feasible due to its relatively wide band gap of 5.5 eV, which is wider than that of silicon 1.14 eV. Fusion plasma diagnostics based on a diamond detector, such as a neutral particle analyzer[15-20], a recoiled proton detector[21, 22], and a deuterium-tritium (D-T) neutron detector[23] based on $^{12}C(n,\alpha)^{9}Be$ reactions[24] have been developed. To measure the ion temperature of 9 keV through D-T neutron energy spectrum broadening[25], the energy resolution of the detector to the D-T neutron should be less than 4%[26]. Previously, D-T neutron spectrometers based on diamond detectors were developed using natural diamond crystals and an energy resolution of ~2% was achieved [23, 27-29]. Although diamond detectors based on natural diamonds have been utilized and shown high-energy resolution, they have difficulties of cost, stable availability and uniformity of performance. Subsequently, the artificial synthesis of detector-grade

diamonds due to chemical vapor deposition became possible due to technological innovation[30-32]. By the development of a diamond detector based on single crystal chemical vapor deposition (s-CVD), the energy resolution for D-T neutrons of ~1% was achieved[33-35]. However, the issues of stable supply, cost, the uniformity of performance and stable availability of the detectors are important, especially in constructing a diamond detector array. The commercialization of diamond detectors is awaited to ensure stable supply and low cost. Recently, a CVD diamond detector became commercially available from CIVIDEC[36]. Therefore, we need to check the uniformity of commercial CVD diamond detector performance. In the Large Helical Device (LHD), plasma experiments using deuterium gas have been done since 2017[37, 38]. These were the first deuterium experiments in large-sized stellarator/helical systems. Therefore, advances in energetic particle confinement were expected[39-41] through the neutron diagnostics[42-50] because neutrons are mainly created by so-called beam-thermal reactions [51]. Energetic particle confinement research, e.g., energetic particle confinement in magnetohydrodynamic quiescent plasmas[52-54], visualization of energetic particle transport[55-60], and demonstration of MeV ion confinement[61, 62], has progressed[63, 64]. Recently the beam ion energy spectrum has been studied using D-D neutron energy spectrometers[65-69]. Understanding of beam ion confinement will progress by measurement of the energy spectrum of charged particles produced by D-D reactions, i.e., tritons, protons, and ^{3}He, by D-T reactions, i.e., alpha particles, and by p-^{11}B reactions, i.e., alpha particles, because their energy has information on beam or MeV ion energies. Also, the D-T neutron energy spectrum can provide information on 1 MeV triton anisotropy. Moreover, understanding a tritium inventory is one of the important tasks[70-72]. An tritium inventory has been mainly compiled, based on annual measurement, using a tritium imaging plate technique[38, 73, 74]. A tritium production rate in each discharge has been evaluated[75] by the CONV_FIT3D code[76]. A time-resolved measurement of escaping triton flux can make progress in understanding the tritium inventory. This paper describes the performance and reproducibility of commercially available s-CVD diamond detectors and their installation as fusion product diagnostics.

2. Commercially available chemical vapor deposition single crystal diamond detector response to alpha particles

This paper surveyed commercially available s-CVD diamond detectors (B12, CIVIDEC)[77] shown in Fig. 1 a. We obtained the s-CVD diamond detectors' response to alpha particles using an alpha particle calibration source in a laboratory in the LHD building. Figure 1 b and c shows the setup for this calibration. The diamond detector was placed inside the vacuum vessel, and we put the alpha particle calibration source in front of the detector at a distance of 1 mm. The alpha particle calibration source contained ^{241}Am 100 Bq, ^{244}Cm 50 Bq, and ^{237}Np 150 Bq on 20th April 2022. Note that the alpha particle energy of ^{241}Am, ^{244}Cm, and ^{237}Np, are 5.49 MeV, 5.80 MeV, and 4.96 MeV, respectively. The diamond detector was connected with a charge sensitive preamplifier (Cx-L, CIVIDEC)[78] through an SMA J-J connector. Note that the Cx-L output a semi-Gaussian shape pulse having a width of ~150 ns. The pulse width is narrow compared with the pulse width outputted by a conventional shaping amplifier of ~1 μs [79]. Therefore, a relatively high-counting rate operation was possible using the Cx-L preamplifier. In addition, the Cx-L can accept a relatively long cable between the diamond detector and preamplifier of up to 1000 pF. The preamplifier signal was transferred to the data acquisition system (DAQ) using a double-shield 15 m 50-Ohm cable (3D-FB). The output signal was

117 acquired by the DAQ, consisting of a 14-bit and up to 500 MHz sampling rate analog to digital
118 converter, and a field programmable gate array, providing online and offline pulse shape
119 analysis functions (APV8508-14, Techno AP)[80]. Here the charge integral of one pulse Q_{total}
120 was calculated online. The high voltage +360 V, corresponding to 0.72 V/μm, to the diamond
121 detector was applied by a high voltage module (428, ORTEC). The power to the preamplifier
122 was provided by a low-voltage-ripple switching power supply (PLD-18-2, Matsusada Precision
123 Inc.). The typical pulse count rate obtained in this calibration was 30 counts per second. The
124 pileup effect was negligibly small. The Q_{total} spectrum obtained by this calibration is shown in
125 Fig. 2a. The peaks on ~4400, ~5100, and ~5400 channels correspond to 4.96 MeV, 5.49 MeV,
126 and 5.80 MeV, respectively. Figure 2b shows the relation between Q_{total} and alpha particle
127 energy E_α. The energy calibration of the diamond detector using three peaks was performed
128 using the linear function E_α [keV]= $a \times Q_{total} + b$. The coefficient of (a, b) is (1.155, -1.289),
129 (1.179, -1.353), (1.147, -1.301), and (1.167, -1.254) for B120033, B120034, B120035, and
130 B120036, respectively. It is worth noting that the difference in the coefficient obtained in four
131 different detectors is only 3%. Figure 2c shows the energy resolution (full width at half
132 maximum)/(peak position) for each detector for respective E_α. The energy resolution is 1% to
133 3%. Here, ther energy resolution was relatively lower than the previous report of s-CVD
134 diamond detector [81] due to the shorter distanve between the alpha source and the diamond
135 detector. It was found that the performance of each commercially available s-CVD diamond
136 detector was well aligned.

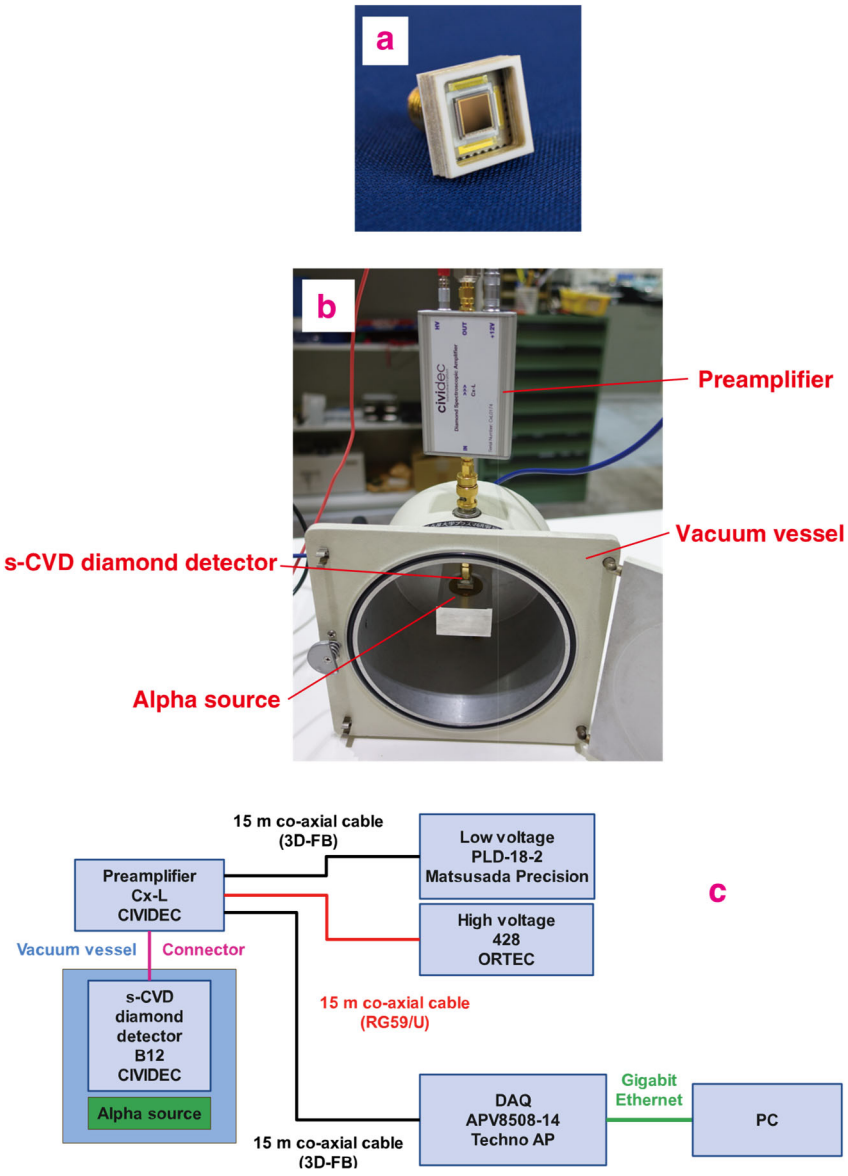

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Figure 1. a) s-CVD diamond detector B12 b) Experimental setup of s-CVD diamond detector calibration using ^{241}Am, ^{244}Cm, and ^{237}Np alpha sources. c) Block diagram for alpha calibrations.

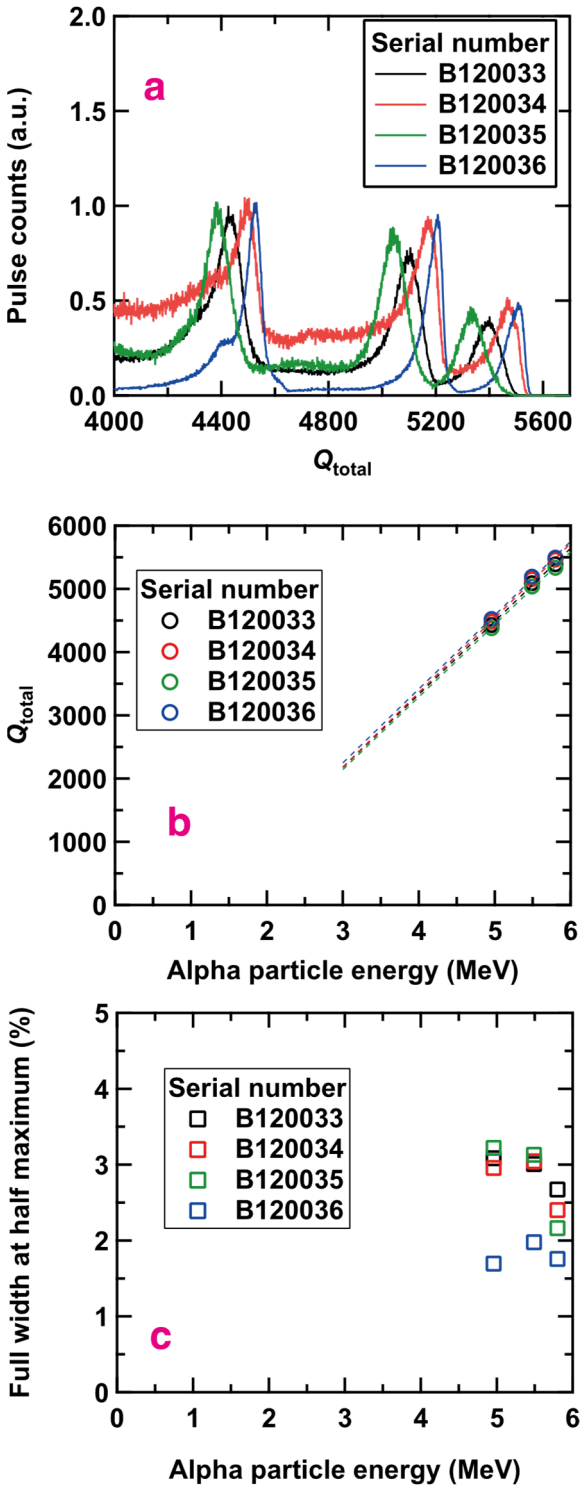

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Figure 2. a) Charge integral of one pulse (Q_{total}) spectrum obtained by four s-CVD diamond detectors in alpha calibration. b) Dependence of Q_{total} on alpha particle energy. c) Energy resolution of each s-CVD diamond detector for alpha source.

3. Commercially available chemical vapor deposition single crystal diamond detector response to D-T neutrons

The response of s-CVD diamond detectors to D-T neutrons was obtained in the accelerator-based D-T neutron source OKTAVIAN at Osaka University[82]. Figure 3 shows the setups for D-T neutron calibration in OKTAVIAN. A 250 keV/90 μA deuteron beam was injected into a 5 μm thick tritium-occlusion titanium target. The typical D-T neutron emission rate from the target was 10^9 n/s, and the measurement time was set to 15 minutes. The diamond detector was placed at the front or the side of the titanium target. The diamond detector was connected with the charge sensitive preamplifier (Cx-L, CIVIDEC) through the SMA J-J connector. The output signal was transferred to the DAQ (APV8508-14, Techno AP) using a double-shield 15 m 50-Ohm cable (3D-FB). The high voltage +360 V to the diamond detector was applied by the high voltage module (428, ORTEC). The power to the preamplifier was provided by switching power supply (PLD-18-2, Matsusada Precision Inc.). Here, the DAQ, high voltage module, and power supply were located outside a high-intense neutron irradiation room to avoid the irradiation effect[83].

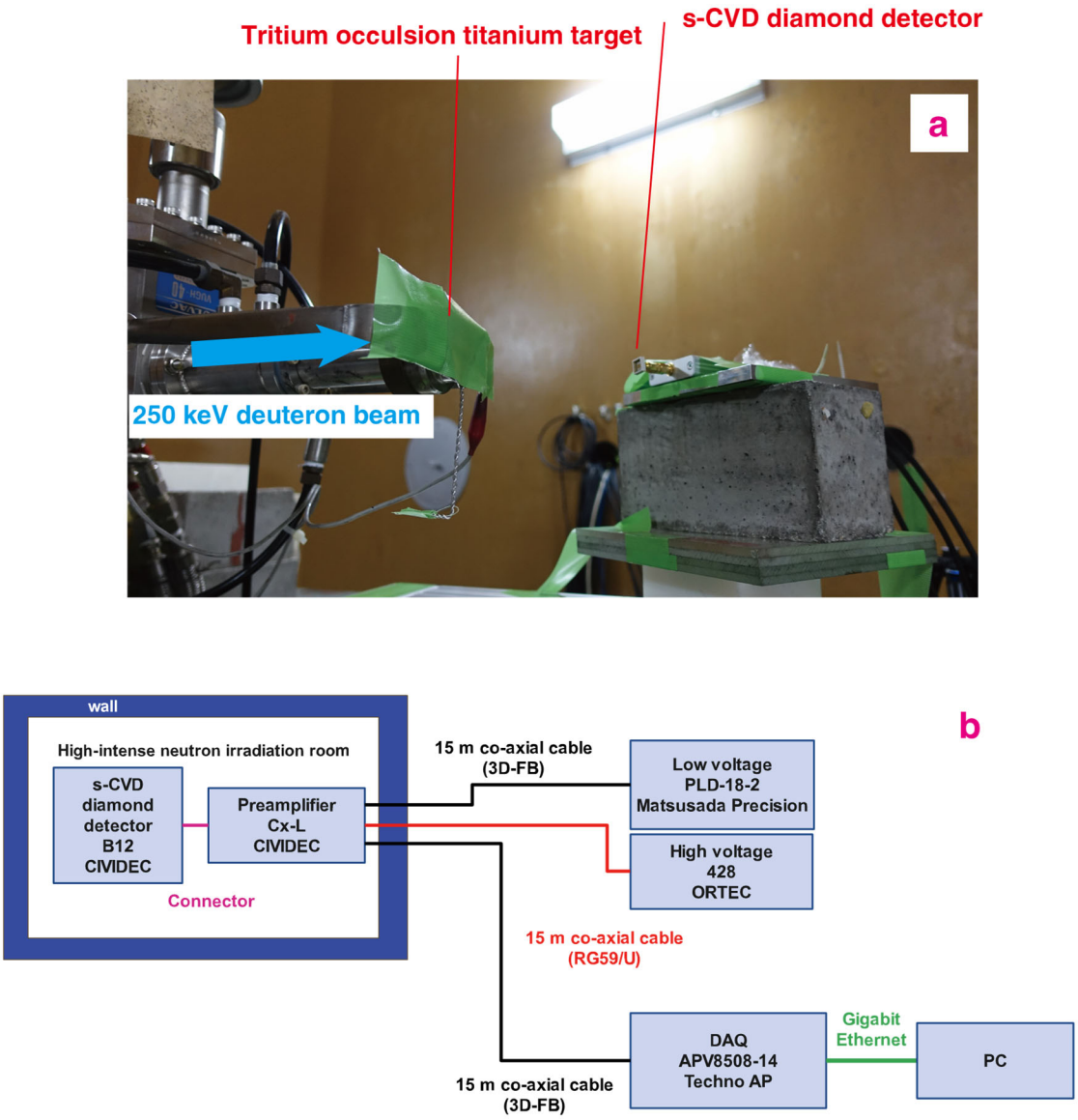

Figure 3. a) Experimental setups for D-T neutron measurement using s-CVD diamond detector in OKTAVIAN in Osaka University. b) Block diagram for D-T neutron measurement.

First, the s-CVD diamond detector response to the D-T neutrons was obtained by changing the detector angle with respect to the beam axis at 0, 27, 48, and 81 degrees. The typical pulse counting rate in this experiment was 800 counts per second. Therefore, the pileup effect was negligibly small, ~0.01%. Figure 4a shows the Q_{total} spectra obtained by the diamond detector (B120033). The peak at approximately 7000 channels corresponded to a $^{12}C(n,\alpha)^{9}Be$ reaction. The position of the $^{12}C(n,\alpha)^{9}Be$ reaction peak shift and broadness of the peak change depended on the detector angle, due to the D-T neutron spectrum at the detector position. The full width at a half maximum of the $^{12}C(n,\alpha)^{9}Be$ reaction peaks were 4.6%, 3.8%, 3.1%, and 2.1% in 0-, 27-, 48-, and 81-degree cases, respectively. The main reason for the broadening of the Q_{total} peak might habe been the broadening of the D-T neutron spectrum caused by the beam deuteron

energy spectrum inside the thick tritium target. To evaluate the energy resolution of the diamond detector, we calculated the neutron spectrum at the detector position, in each case using the following method. Using the TRIM code[84], the deuteron beam energy spectrum was calculated by considering deuterium beam attenuation inside the tritium target. The source D-T neutron spectrum was calculated using the deuteron beam energy spectrum and a D-T fusion cross section[85]. A Monte Carlo N Particle (MCNP6) code [86] was utilized to calculate three-dimensional neutron transport inside a high-intense neutron irradiation room. Figure 4b shows the neutron energy spectrum at the detector position obtained by the calculation. Energy shift and energy broadening of the D-T neutron spectrum were obtained. By comparing the experimentally obtained Q_{total} peak width and calculated neutron spectrum peak width at 81 degrees case, the energy resolution of the detector was obtained at 1.7%. The detection efficiency for 14 MeV neutrons was 6×10^{-4} [pulse counts cm^{-2}].

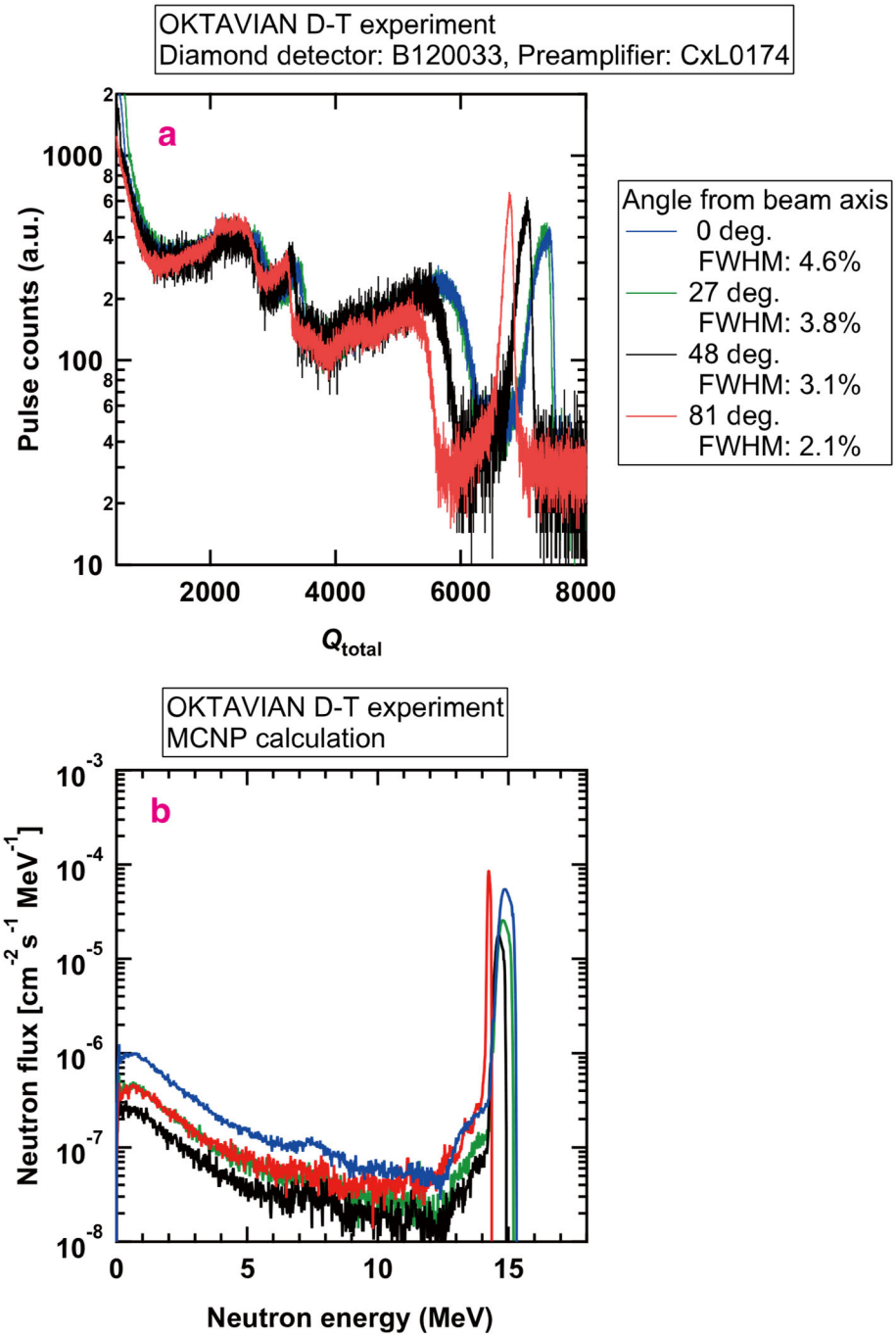

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Figure 4.a) Charge integral of one pulse (Q_{total}) spectrum obtained by the s-CVD diamond detectors in D-T neutron calibration. Detector angle respects to the beam axis changed from 0 degrees to 81 degrees. b) Neutron flux at the s-CVD diamond detector position in OKTAVIAN calculated by three-dimensional neutron transport calculation MCNP6 code.

4. Uniformity of s-CVD diamond detector for D-T neutron measurement and applicability to LHD

We compared the Q_{total} spectrum obtained by the s-CVD diamond detector B12 (B120033) to that obtained by s-CVD diamond detectors (B120034, B120035, and B120036) at 48 degrees (Fig. 5a). The peak due to the $^{12}C(n,\alpha)^{9}Be$ reaction was located between 6762 to 7316 channels, therefore, the difference was only within 7.5%. These detectors had uniform quality. The diamond detectors had to be located in the vacuum vessel to measure the charged fusion product. Although the B12 can work under ultra-high-vacuum conditions, the preamplifier should be operated outside the vacuum due to outgas and heat removal issues. In the LHD case, the B12 will be placed on the first wall, and the preamplifier will be placed on the diagnostics port. The distance between the B12 and preamplifier positions will be approximately 7 m. Therefore, we checked the signal attenuation and noise level using a 7 m vacuum-tight coaxial cable. Here we used a 50-Ohm ultra-vacuum-tight coaxial cable capable of high-frequency signal measurement (MWX 313, Junkosha)[87]. The capacitance of the 7 m MWX313 cable was 560 pF. The standard insertion loss was 2.9 dB/m for a 1 GHz signal. The pulse height spectra obtained in D-T neutron measurement with and without the 7 m cable are compared in Figure 5b. Even though the pulse height almost halved due to the 7 m cable, the energy resolution degradation was only 0.4%. Note that the signal attenuation might have been due to signal dissipation, due to relatively large capacitance[78].

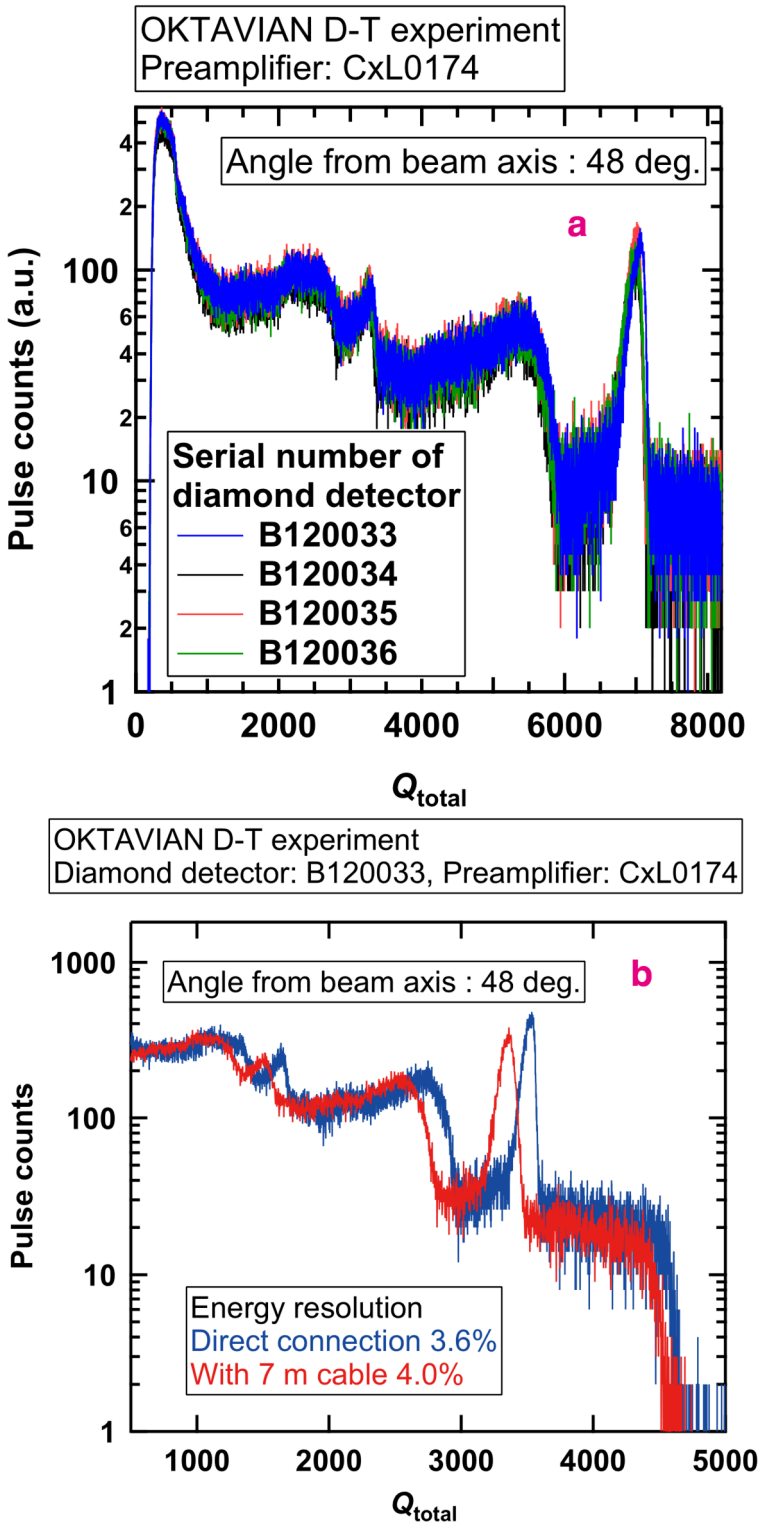

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Figure 5. Charge integral of one pulse (Q_{total}) spectrum obtained by four s-CVD diamond detectors in D-T neutron calibration. $^{12}C(n,\alpha)^{9}Be$ peak is observed at 7000 channels. The detector angle to the beam axis was 48 degrees. b) Pulse height spectrum obtained with and without 7 m cable between diamond detector and preamplifier. The degradation of energy resolution for $^{12}C(n,\alpha)^{9}Be$ peak by 7 m cable is only 0.4%.

5. Installation of commercially available single crystal chemical vapor deposited diamond detector for fusion product measurement in Large Helical Device

5.1 Searching for suitable location for fusion products measurement

The location of diamond detectors was decided, based on a collisionless Lorentz orbit following calculation LORBIT,[88] which is widely used in tokamaks[89-92] and stellarators[92-96]. We considered charged fusion products, i.e., D-D fusion born 1 MeV tritons, D-D fusion born 3 MeV protons, D-T fusion born 3.5 MeV alpha particles, and p-^{11}B fusion born ~4.0 MeV alpha particles[97]. The magnetic field configuration was chosen to be a toroidal magnetic field strength B_t of 2.75 T, and the magnetic axis position R_{ax} of 3.60 m, because approximately 90% of the neutron amount was produced in this configuration[38, 98]. The birth profiles of charged particles were based on the FIT3D-DD code[51, 99, 100], and the birth profile of alpha particles was based on the FBURN code[101]. We launched 10^7 particles in each case and saw the loss points of particles on the vacuum vessel and divertor. Figure 6b shows the lost position of particles in 1 MeV tritons with the magnetic field direction from counterclockwise from the top view. Here the lost points appeared on one side of the helical coil due to the gradient *B* drift. Figure 6c shows the lost position of particles in 1 MeV tritons with the magnetic field direction of clockwise from the top view. The lost points moved opposite the helical coil side when we changed the magnetic field direction from counterclockwise to clockwise from the top view[102]. We chose four positions suitable for detecting charged fusion products using a virtual reality system[103, 104]. The locations of the detectors (*x*, *y*, *z*) were (2507mm, 1900 mm, 1080 mm), (3145 mm, -64 mm, -1080 mm), (2405 mm, 1516 mm, 774 mm,), and (2837 mm, 187 mm, -774 mm). Here the original position was set to be the center of the LHD machine, the x-axis set to be 3.5 sections, and the y-axis set to be 1 section of LHD. In addition, we were able to measure 14 MeV neutrons using the $^{12}C(n,\alpha)^{9}Be$ reaction, using this diamond detector for a triton burnup study in LHD[61]. By estimating a 14 MeV neutron flux using the MCNP6 code [105] considering a maximum triton burnup ratio of 0.45% [62], the expected relative 14 MeV neutron flux in this position was 10^{-5} [cm^{-2} per source D-T neutrons][106]. The pulse counting rate in the discharge, with a total neutron rate of ~10^{15} [n/s], which was the typical total neutron rate in deuterium-NB-heated LHD deuterium plasma[63], was expected to be 27 kcps.

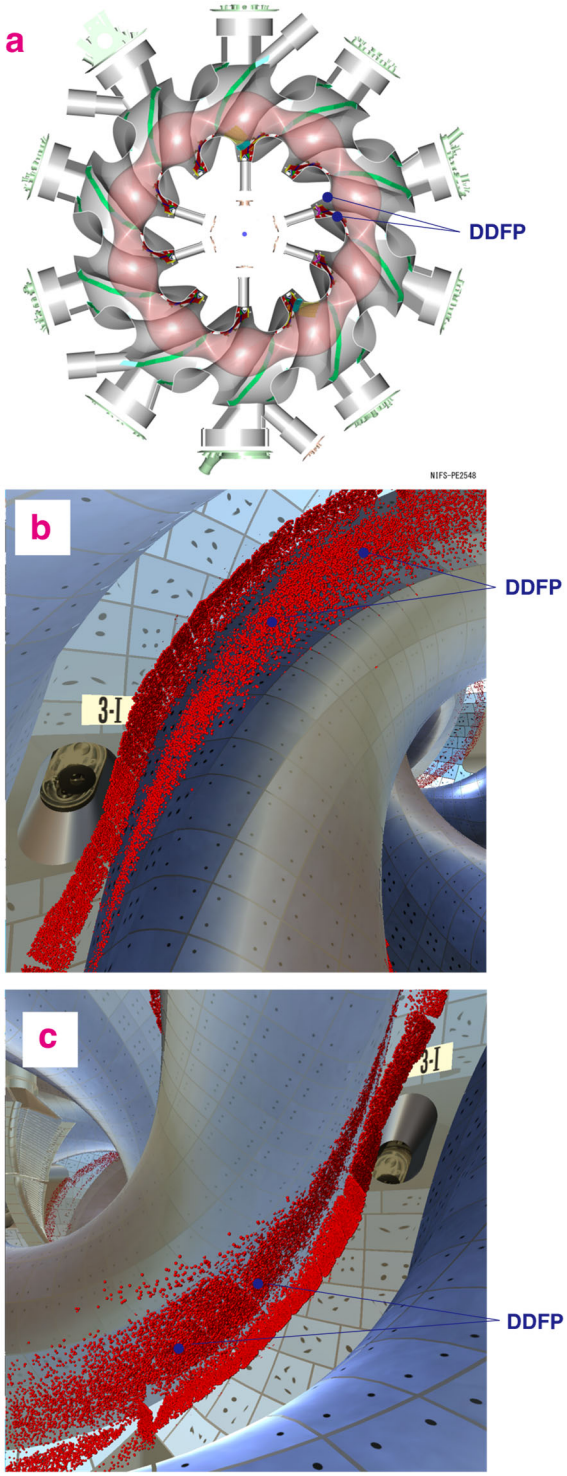

Figure 6. a) Bird's eye view of the Large Helical Device and the diamond detector for fusion products (DDFP) position. Loss points of the 1 MeV triton on the first wall and DDFP position in the b) counterclockwise and c) clockwise direction of the toroidal magnetic field from the top view.

5.2 Design of diamond detector for fusion products

We installed diamond detectors for fusion products (DDFP) consisting of four-s-CVD detectors in LHD. Fig. 7 shows the setup of the DDFP. The protective tile of the LHD first wall was modified to mount the B12 detector. A thin titanium foil of 2 μm thickness was inserted in the front of B12 detector to prevent the low-energy particles and x-rays from entering. The hollow cylindrical cover with a notch was for avoiding graphite stacking on the B12 detector. The 7 m MWX313 cable covered by an SUS316 flexible tube was used to connect the B12 detector to transfer the signal to the diagnostics port. To avoid electrical noise, the preamplifier Cx-L is directly connected to the SMA feedthrough flange on the diagnostics port. The preamplifier signal is transferred by <50 m double shield 50-Ohm cable to the diagnostic rack on the torus hall. The signal is acquired by a 14-bit 500 MHz sampling ADC (APV8508-14, Techno AP). The Q_{total} data of each pulse with the timestamp analyzed online will be stored in the LHD database. An external controllable high voltage module having a logging function applies high voltage (APV3304, Techno AP)[107].

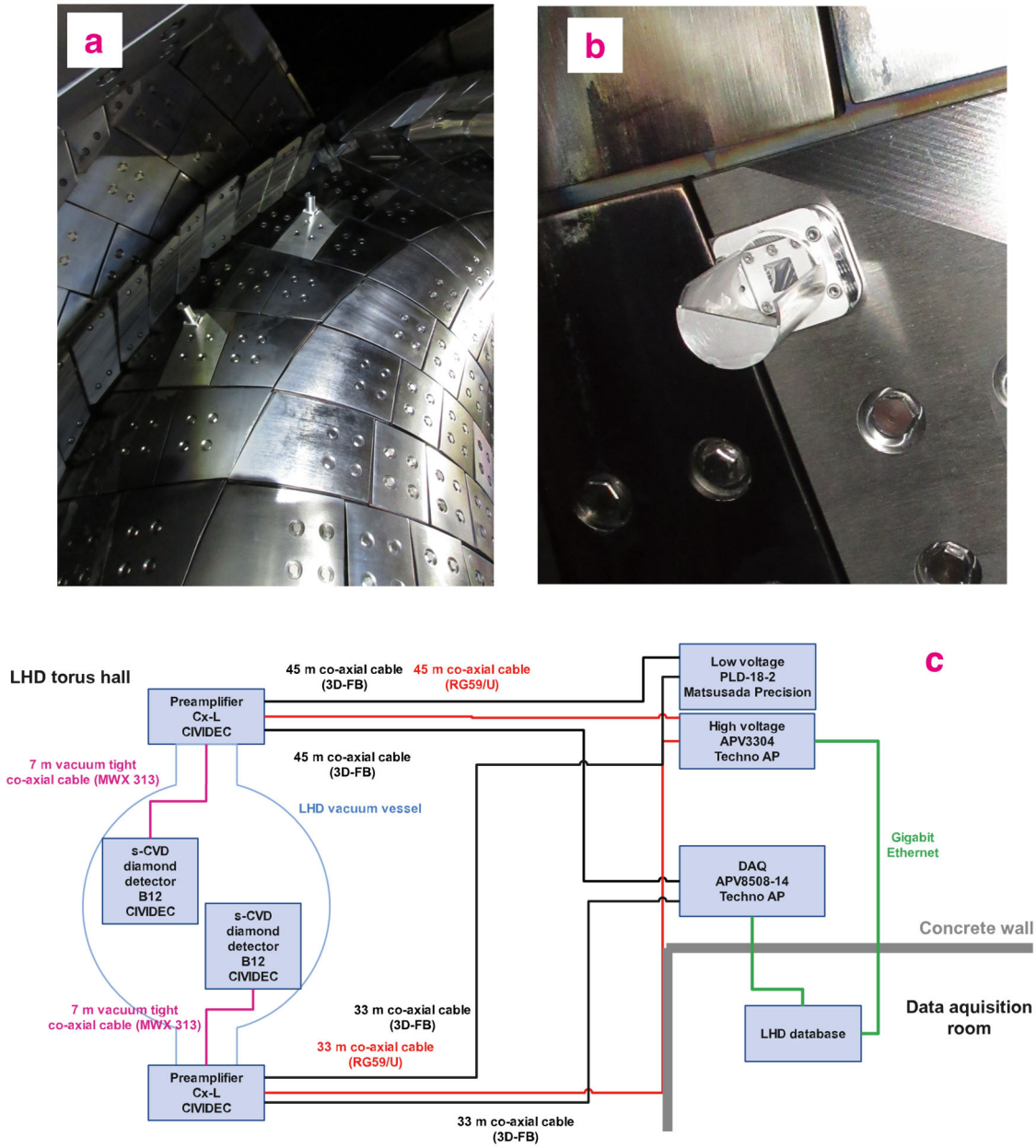

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Figure 7. a) Diamond detector for fusion product (DDFP) installed in the upper side of LHD and b) zoomed photo. c) Block diagram of data acquisition and control of DDFP installed in LHD.

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250 ## 6. Summary

251 To understand energetic particle confinement in LHD, a diamond detector for fusion products
252 has been installed. First, the performance of commercially available s-CVD diamond detectors
253 and their uniformity were surveyed using alpha particle and D-T neutron sources. The
254 dependence of the total charge in one pulse signal as a function of alpha particle energy shows

that the difference in slope and offset is only 3%. The energy resolution for alpha particle measurement is less than 3%. The results of D-T neutron measurement show the energy resolution for 14 MeV neutrons is 1.7%, which is enough for fuel ion temperature measurement in fusion burning plasmas, and the pulse height spectrum obtained by four detectors is almost identical. A Lorentz orbit calculation plotted with a virtual reality system is capable of choosing the diamond detector positions inside the LHD vacuum vessel. Further progress of energetic ion confinement in LHD by the DDFP is expected.

Acknowledgments

We are pleased to acknowledge the assistance of the LHD Experiment Group.

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