氏　　　名	XU XIUQING
学位（専攻分野）	博士（工学）
学 位 記 番 号	総研大甲第 2306 号
学位授与の日付	2022 年 3 月 24 日
学位授与の要件	高エネルギー加速器科学研究科　加速器科学専攻 学位規則第6条第1項該当
学 位 論 文 題 目	Development of a high flux capability neutron detection system in harsh environment using a CVD diamond detector
論 文 審 査 委 員	主　査　　波戸　芳仁 加速器科学専攻　教授 佐波　俊哉 加速器科学専攻　教授 齋藤　究 加速器科学専攻　准教授 岸本　祐二 加速器科学専攻　准教授 岩瀬　広 加速器科学専攻　准教授 萩原　雅之 国立研究開発法人量子科学技術研究開発機構 量子ビーム科学部門　次世代放射光施設整備開 発センター　基盤技術グループ　グループリーダー

（様式３）

博士論文の要旨

氏　　名　XU XIUQING

論文題目 Development of a high flux capability neutron detection system in harsh environment using a CVD diamond detector

Chemical Vapor Deposition (CVD) diamond detector is an attractive semiconductor detector, due to their advantages, such as large bandgap, high electron-hole mobility, low leakage current, excellent timing resolution, outstanding radiation hardness, and so on. Especially, the low gamma sensitivity and the outstanding radiation hardness of a diamond detector make it a suitable candidate for neutron measurements at harsh radiation environment such as Fukushima Daiichi nuclear power plant (NPP), Super KEKB, J-PARC, and LHC.

In this research, a high flux capability neutron detection system in harsh environment using a CVD diamond detector was developed. We investigated the applicability of two CVD diamond detectors coupled to a thin layer of ^{6}LiF for the detection of thermal neutrons, one is commercially available and the other is prepared based on our request, were used for test of basic properties and actual response measurement. Both detectors with equal active areas of 10 mm^{2} were manufactured by CIVIDEC (Vienna, Austria). The detectors were characterized in terms of current–voltage characteristics, charge collection efficiency (CCE), and α-particle energy resolution. The leakage current of the 140-μm-thick diamond detector was very low, below 20 pA, up to an electric field intensity of 5 kV/cm. For the 25-μm-thick diamond detector, the leakage current was below 10 pA at electric fields below 15 kV/cm. The CCEs of the detectors were measured using a mixed α-source, composed of ^{148}Gd (3.183 MeV), ^{241}Am (5.486 MeV), and ^{244}Cm (5.805 MeV). The maximum CCEs of the 140 μm thick detector under the irradiations with ^{148}Gd, ^{241}Am, and ^{244}Cm were measured to be 91.6%, 96.6%, and 96.9%, while those for the 25 μm thick detector were 91.1%, 95.7%, and 96.0%, respectively.

The γ-ray irradiation experiments were performed at dose rates of 0.693 to 107 Gy/h with a conventional analog circuit. The apparent energy deposition of the 140-μm-thick detector exceeded the peak energy (2.73 MeV) of triton produced in the ^{6}Li (n, t) α reaction at 6.36 Gy/h owing to signal pile-up effects, which enhance the spillover between the pulse-height distributions of γ-ray and neutron events. However, the 25-μm-thick diamond detector did not exhibit serious pile-up effects and maintained the neutron/γ discrimination capability with the pulse-height distributions even at 107 Gy/h. This indicates that the 25-μm-thick diamond detector can be used for neutron measurements in the presence of a strong background of γ-rays beyond 100 Gy/h even with a conventional analog circuit.

For minimize the pulse pile-up events and measuring the transient current signals with a few nanoseconds' durations, we used a fast current-sensitive preamplifier (CIVIDEC C2-TCT) with 2 GHz bandwidth and 40 dB gain. The preamplifier output signals are recorded with a 10-bit waveform digitizer (Agilent-Acqiris DC282) which has a bandwidth of 1.5 GHz and at a sampling rate of 2 GS/s. To investigate the basic characteristics of the digital system, the detection of the α-particles from a mixed α-source (^{148}Gd, ^{241}Am, ^{244}Cm), γ-ray from a ^{60}Co source with dose rates of 0.693 to 107 Gy/h, thermal neutrons source using the KEK graphite pile with an ^{241}Am (37 GBq)-Be source were performed. The Full-Width-at-Half-Maximum (FWHMs) of the signals are less than 5 ns which is around several hundred times faster than the signals from those analyzed in the traditional analog circuit system. It is noted that the signal doesn't exhibit jagged noise or a long tail as some scintillators do. The two CVD diamond detectors show slightly different energy resolutions; 2.8% for the 140 μm thick one and 3.9% for the 25 μm thick one at the ^{241}Am-α energy (5.486 MeV). Both detectors did not exhibit pile-up effects even exposed to intense γ-rays with dose rates of 107 Gy/h. The pulse height distribution show broader energy resolutions compared to those analyzed in the traditional analog circuit system, these energy resolutions are, however, still sufficient to determine an appropriate threshold to discriminate γ-ray events from neutron events.

The responses of the detectors to thermal neutrons were studied through measurements and Monte Carlo simulations with the PHITS code. The measurements of thermal neutrons were carried out using thermalized neutrons from an ^{241}Am–Be neutron source in the radiation calibration facility at KEK. A ^{241}Am–Be neutron source also produces a strong field of γ-rays with energies up to 4.4 MeV. The neutron source was at the center of a graphite pile, which consisted of a high-purity carbon, producing a standard thermal neutron field. The experimental results and simulation results well agreed. While the distance was set as 47 cm, the thermal neutron detection efficiencies of the 25 μm thick and 140 μm thick diamond detectors with analog system were $1.04\times10^{-4}\pm8.87\times10^{-6}$ and $1.03\times10^{-4}\pm 8.83\times10^{-6}$ cps/nv, respectively. The thermal neutron detection efficiencies of the 25-μm-thick diamond detectors with TCT-Acqiris digital system were $1.00\times10^{-4}\pm 8.54\times10^{-6}$ cps/nv. Meanwhile, the distance was set as 69.60 cm, the thermal neutron detection efficiencies of the 25-μm-thick diamond detectors with TCT digital system were $9.85\times10^{-5}\pm1.09\times10^{-5}$ cps/nv. Even the distance was changed to 69.6 cm, only a small (~5%) difference is shown in the measured efficiency. The almost same detected efficiency between the analog system and TCT digital system indicate that the pulse height processing method for TCT-Acqiris digital system is reliable.

In order to test the TCT-Acqiris digital system in a mixed source which content gamma and neutron source, the responses of the diamond detectors were experimentally performed in the electron linear accelerator facility of the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS). As the thermal neutron efficiency has been measured, we can estimate the thermal neutron flux according to the efficiency and counting rate. Then, the thermal neutron flux is $1.86\times10^5\pm 3.75\times10^4$ $s^{-1}cm^{-2}$ at average current 3.5 μA operation. The diamond detector successfully used to measure the neutron flux in a mixed environment based on a Compact Accelerator-based Neutron Sources.

In order to measure the fast neuron, the experimental and simulated response to the Bonner sphere with different energy was studied. Bonner sphere spectrometer (BSS) used in this research have five diameters i.e 0(bare), 40, 70, 110, 190 mm. The CVD diamond detector is located at the center of BSS that used as neutron detector. The Bonner sphere response functions were simulated using the Monte Carlo code-- PHITS code. Bonner sphere response functions were used to unfolding the energy spectrum measured in the STF tunnel.

Finally, the authors conclude above results and discuss possible application based on knowledge from these results.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis defense

博士論文審査結果

Name in Full
氏　名　XU XIUQING

Title
論文題目　Development of a high flux capability neutron detection system in harsh environment using a CVD diamond detector

化学蒸着法（CVD）ダイヤモンド検出器は、大きなバンド幅、電子と空孔の高い移動度、優れた時間分解能、高い放射線耐性などの点で有望な放射線検出器である。特にガンマ線に対する低い感度と、高い放射線耐性の点から、放射線強度の高い場での応用が見込まれる。出願者はこの CVD ダイヤモンド検出器を ^{6}LiF 薄膜を組み合わせたものについて、福島第一原子力発電所の廃炉作業における格納容器内や、大出力加速器のトンネル内などの、ガンマ線バックグラウンドが極めて高い環境下で中性子を測定する検出器として用いることを発案し、実験および計算により、その特性を調べて論文としてまとめている。この研究ではおおきく二つの工夫が行われている。一つは市販品であった 140μm より薄い 25μm の CVD ダイヤモンド検出器を制作したことである。これにより、^{6}Li(n,t)α 反応から発生する粒子の測定能力を維持しつつ、ガンマ線に対する感度を十分低く抑えることができた。この 25μm の CVD ダイヤモンド検出器のガンマ線感度抑制効果を実験と計算で実証し、ガンマ線感度を抑制することにより、広い線量範囲にわたり単純な波高弁別により中性子による信号のみを取得できることを示した。二つ目の改良として、従来型のアナログの信号処理系に代えて、電流増幅型プリアンプと波形デジタイザからなる高速の信号処理系を CVD ダイヤモンド検出器の信号読みだしに採用し、信号の速さを活かした高計数率対応の測定系を構成した。2 種類の厚さの検出器と 2 種類の信号処理系、計 4 種類の組み合わせに対して、線源(^{148}Gd, ^{241}Am, ^{244}Cm)からのα線、^{60}Co 線源からのガンマ線(0.693-107Gy/h)、^{241}Am-Be を黒鉛パイルに設置して発生させる熱中性子への応答を実験的に取得し、シミュレーションを併用してその応答について詳細に調べた。これにより、検出器のガンマ線と熱中性子応答の定量化を行い、検出器の適用範囲の議論を行なうことができた。また、電子加速器のターゲットやビームダンプ近傍において、ターゲットから発生するパルス状の減速中性子の測定と、多数の球形の減速材を用いたビームダンプから発生する中性子のスペクトル測定について、CVD ダイヤモンド検出器の適用性を検討した。

審査会では、出願者は研究内容を英語で発表し、質疑に対しても英語で的確に応答を行った。本研究の研究成果について国際会議 IEEE-NS において発表を行うとともに、査読付き英文雑誌に投稿済みであり、国際シーンで研究活動を行ためにに十分な英語能力を有していると判断された。

以上により論文の趣旨および内容は博士論文として十分であると判断され、審査委員全員一致で本審査を合格とした。