Diagnostic of Fusion Neutrons on EAST Tokamak Using 4H-SiC Detector

B. Hong, G. Q. Zhong, L. Q. Hu, R. X. Zhang, R. J. Zhou, K. Li, L. S. Huang, and W. K. Chen

***Abstract*—Due to significant radiation hardness, thermal properties, low sensitivity to gamma rays, and fast response, the 4H-SiC detector exhibits promising properties in measuring the neutron production in the high-power fusion devices. To demonstrate the potential value of the 4H-SiC detectors as a neutron flux monitor and a neutron spectrometer on experimentally advanced superconducting tokamak (EAST) during the 2021 EAST deuterium–deuterium plasma experimental campaigns, the 4H-SiC detector covered with a 25-μm-thick ^{6}LiF film 95% enriched in ^{6}Li and the 4H-SiC detector covered with a 1.5-mm-thick polyethylene layer were installed on a viewport located at the mid-plane of port F outside the EAST vacuum vessel and operated continuously during the whole experimental campaign with the goal to measure both the total and the time-dependent neutron emission from the plasma. The results are compared with those obtained with detectors routinely working at EAST (^{235}U Fission Chambers). Despite their small active volumes, the 4H-SiC detectors were able to measure the total and the time-dependent neutron emission with good reliability and stability. The results of this work not only demonstrated the satisfactory performance of the 4H-SiC detector in the harsh environment of a mixed neutron–gamma high-radiation field and strong electromagnetic field, but also its applicability as a neutron spectrometer and a neutron flux monitor for fusion deuterium–plasma experiments.**

***Index Terms*—4H-SiC detector, fusion neutron, neutron diagnostics, tokamak.**

I. INTRODUCTION

THE measurement of neutrons produced by fusion is one of the most important diagnostic methods for deuterium–deuterium (D–D) or deuterium–tritium (D–T) plasma characterizations. Characteristic plasma parameters, such as ion energies, their distributions, and ion temperature, can be extracted from analysis of the measured neutron spectra [1]–[4]. Neutron diagnostics will play an important role in the future of International Thermonuclear Experimental Reactor (ITER). They will provide key information on plasma physics, machine protection, and control issues [5]. The detection of neutrons emitted from ITER plasmas represents a challenge due to a harsh environment of strong radiation exposure (neutron and gamma ray), strong magnetic field, high vacuum, and the operating temperature, which makes the silicon and scintillation detectors that previously applied in tokamaks [the Tokamak Fusion Test Reactor (TFTR), JT-60, experimentally advanced superconducting tokamak (EAST), Joint European Torus (JET)] difficult to meet the requirements [1], [3]–[5]. The development of neutron and radiation detectors capable to withstand ITER working conditions is one of the key issues of fusion neutrons measurement.

Due to its wide bandgap (3.27 eV) and excellent electrical/thermal properties, the silicon carbide (SiC) detector is a potential candidate semiconductor detector used in harsh environments, such as high temperatures, strong radiation, and high neutron flux [6], [7]. Studies have highlighted the high radiation hardness of the SiC detector by observing the effects of neutrons, protons, and heavy-ion irradiation on these detectors and the SiC detector is able to operate the high temperature during the long-term operation [8]–[10]. Furthermore, in recent years, new manufacturing techniques have allowed the production of SiC detectors with a wider range of geometries. The detector responses of these new SiC detectors were characterized in the past with 14 MeV deuterium–tritium (D–T) neutrons and over a wide range of fast neutron energies, showing energy resolutions and efficiencies comparable to those of the diamond detectors [9]. Therefore, for all these characteristics, the use of these detectors is particularly interesting for all those activities where high particle flux must be detected, such as fast neutron detection in thermonuclear fusion.

The objective of this article was to expand the knowledge on neutron measurement with the 4H-SiC detector in the EAST tokamak. In this work, we developed the neutron flux monitor and neutron spectrometer based on the 4H-SiC detectors for simultaneous measurements of the D–D fusion neutron energy and time-dependent neutron emissions in the EAST tokamak. The detection properties of the 4H-SiC detectors are first tested by a radiation source and then they are applied in the measurements of the D–D fusion neutron energy and time-dependent neutron emission rate at EAST tokamak during the 2021 experimental campaigns. The test results are compared with a neutron diagnostic based on the fission

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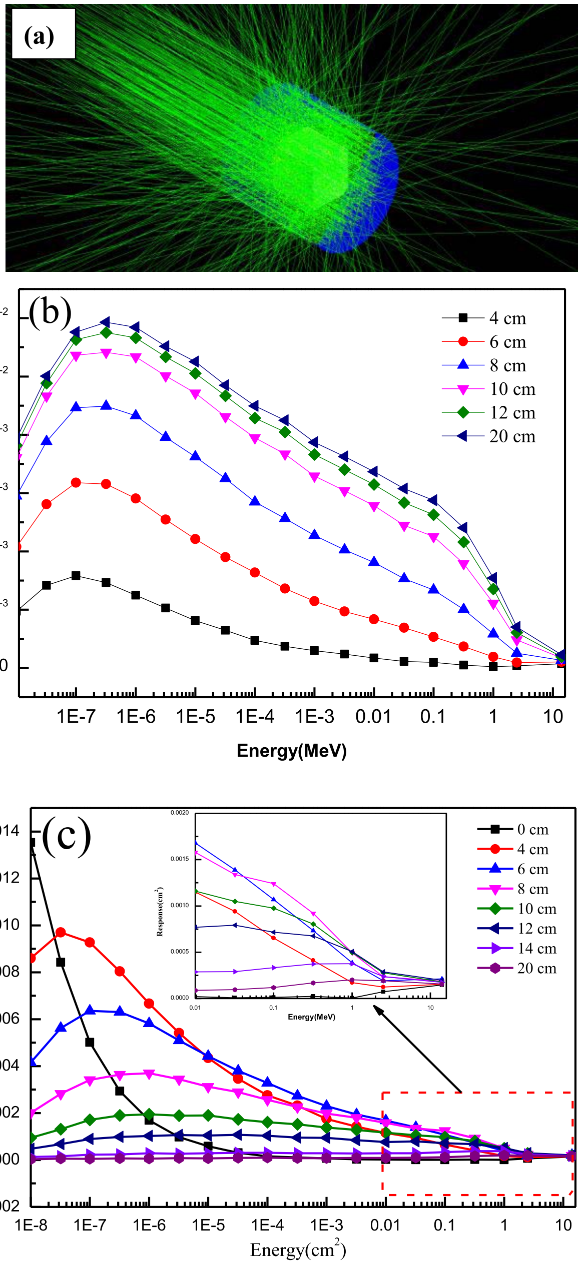

Fig. 1. Responses of the 4H-SiC detector with the ^{6}LiF converter as a function of sizes of the polyethylene cylinder: (a) Geant4 model of the 4H-SiC detector, (b) effect of polyethylene cylinder's diameter, and (c) effect of polyethylene cylinder's length.

chamber at EAST tokamak. Foreseen developments are also discussed.

II. PRINCIPLE OF NEUTRON DETECTION

The 4H-SiC detector can be utilized to detect fast neutrons by means of inelastic and elastic scattering reactions of ^{28}Si and ^{12}C nuclides with neutrons [8]. A layer of hydrogenous converter can be employed over 4H-SiC to further enhance its detection efficiency. This converter and detector setup is known as a proton recoil detector [7]. References have shown that the 4H-SiC detector efficiency will increase significantly with the increase of hydrogenous converter layer thickness and when the thickness of converter reaches a certain value, the detector efficiency decreases due to the self-absorption of proton energy in the converter itself [11], [12]. For the 2.5-MeV D–D neutron, to attain the maximum detection efficiency, the optimized thickness of the converter layer is 100 μm and for 14-MeV D–T neutron, its thickness is 2000 μm [11].

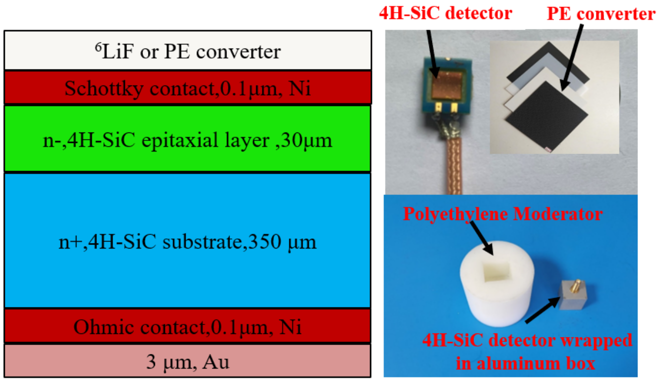

Fig. 2. Schematic diagram and actual drawing of the 4H-SiC detectors.

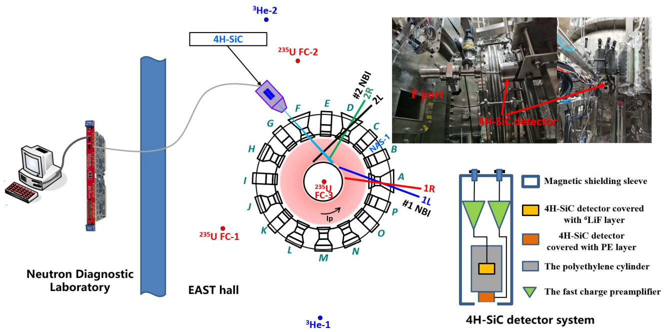

Fig. 3. Neutron flux monitor and neutron spectrometer based on the 4H-SiC detectors installed at the EAST tokamak.

Although the 4H-SiC detector is not sensitive to thermal neutrons, the thermal neutron converter, such as 6-lithium or 10-boron, was used for allowing the 4H-SiC detector to detect thermal neutrons [13]. Among thermal neutron converters, lithium fluoride (^{6}LiF) is the most frequently used thermal neutron conversion material because of its stable chemical properties, relatively high thermal neutron absorption cross section ($\sigma = 942$ b at a neutron energy of 0.0253 eV) and high energies of reaction products. The neutron capture reaction on ^{6}Li results in alpha and triton particle production are as follows:

$$^{6}\text{Li}+\text{n}\rightarrow\alpha(2.05\ \text{MeV})+{}^{3}\text{H}(2.73\ \text{MeV}),\quad Q=4.78\ \text{MeV}.$$

References show that the thermal detection efficiency of the 4H-SiC detector reaches the maximum when the ^{6}LiF thickness is up to 25 μm [13]. Considering that the reaction cross section of ^{6}Li $(n, \alpha)^3$H is low for 2.45 MeV neutrons produced by the reaction D $(d, n)^3$He, the 4H-SiC detector is installed in the center of the polyethylene cylinder to improve the efficiency of the detector for D–D neutrons. The size of the polyethylene cylinder is optimized by using Geant4 simulation. In this simulation, we have used Geant4.10.7 version.

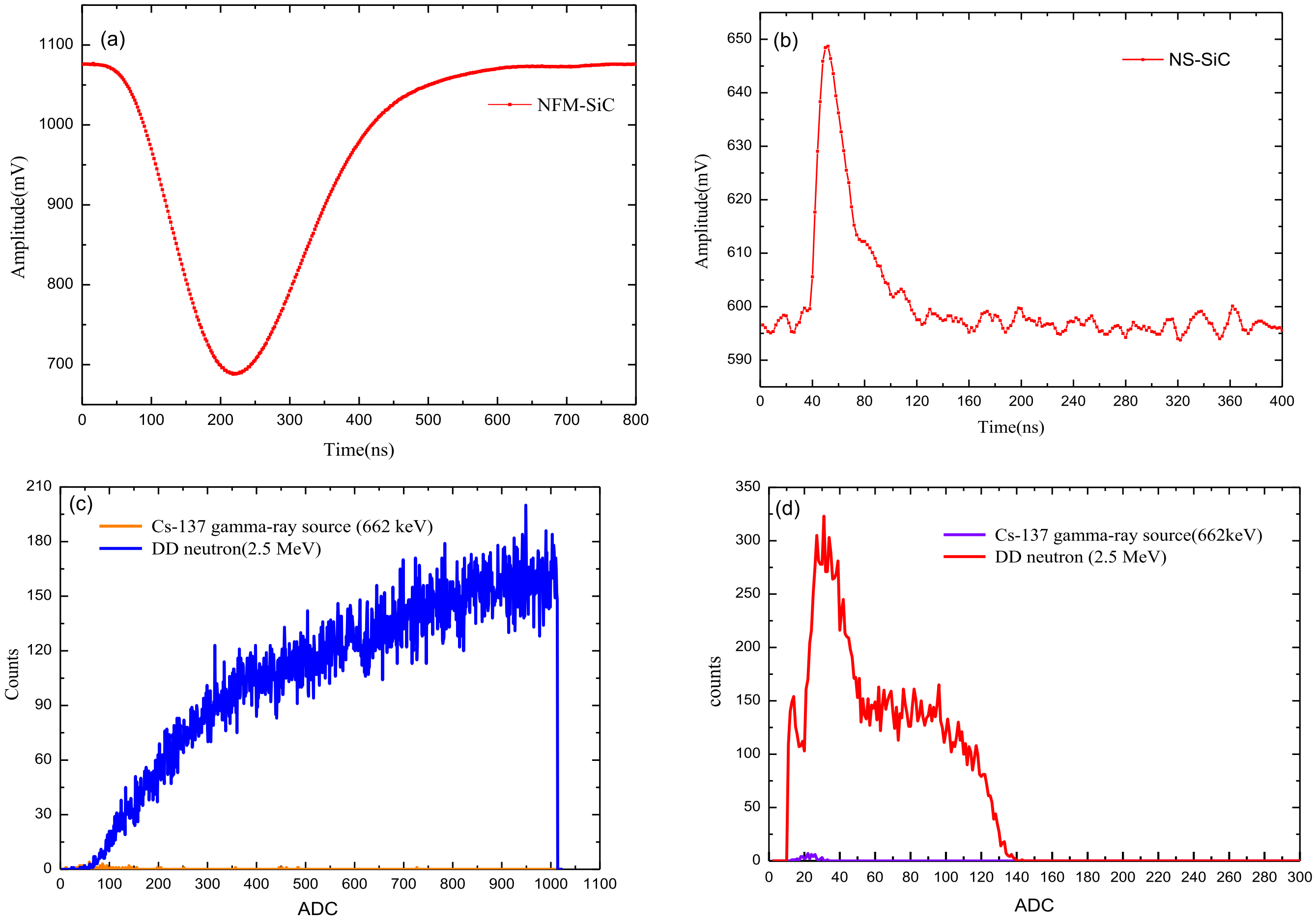

Fig. 4. Pulse signal and the energy spectrum measured by **NFM-SiC** and **NS-SiC** for the D–D neutron generator and ^{137}Cs source: (a) impulse responses of the **NFM-SiC** detector with a FWHM of 200 ns. (b) Impulse responses of the **NS-SiC** detector with an FWHM of 10 ns. (c) 2.5-MeV neutron response spectra and gamma spectra of **NFM-SiC**. (d) 2.5 MeV neutron response spectra and gamma spectra of **NS-SiC**.

The 4H-SiC detector with a 25-μm-thick ^{6}LiF converter is used in this calculation, and the size of the 4H-SiC detector is 5 mm × 5 mm × 380 μm (thickness). The front surface of the polyethylene cylinder is irradiated perpendicular with a parallel beam of mono-energetic neutrons ranging from thermal to 1 MeV, a D–D neutron source of 2.5 MeV, and a 14 MeV D–T neutron source. The number of particles used in the simulation is 1×10^8. The standard physics mode QGSP_BERT_HP has been used. The energy deposit by alpha and triton particle production in the sensitive detector was obtained using the G4Step class. Fig. 1 shows the responses of the 4H-SiC detector with the ^{6}LiF converter as a function of the energy of the incident neutrons. It can be seen in Fig. 1 that the overall response of the 4H-SiC detector increases with the increase of the diameter of the polyethylene moderator and the maximum response of the detector shifts toward the higher energy side with the increase in the length of the polyethylene moderator.

III. MEASUREMENTS SYSTEM

In this work, we constructed two 4H-SiC detectors for neutron flux and energy spectrum measurements in EAST, as shown in Fig. 2. One 4H-SiC detector covered with a 1.5-mm thick polyethylene (PE) layer was used as a neutron spectrometer for measuring the neutron spectrum and neutron emission, which will be referred to as **NS-SiC**. In order to accommodate the measurement of DD and DT neutrons, we have considered 1.5 mm thickness as an optimized one in this work. The active volume of **NS-SiC** is 10 mm × 10 mm wide and 30 μm thickness. Another 4H-SiC detector covered by a 25-μm-thick ^{6}LiF foil was used for measuring the neutron flux, which will be referred to as **NFM-SiC**. The active area of **NFM-SiC** is 5 mm × 5 mm × 30 μm (thickness). Taking into account the size and efficiency of the 4H-SiC detector, the 4H-SiC detector is installed in the center of the polyethylene cylinder with 6 cm in diameter and 8 cm in length. In order to shield the detector from environmental electromagnetic radiation and dust, each of the 4H-SiC detectors was encased in an aluminum box with 1 mm thick. In order to acquire the high-rate measurements by reducing the pile-up probability, neutron signals from the 4H-SiC detectors are amplified by the fast preamplifier. For the **NFM-SiC** detector, the amplification of the detector's signal is done by the CIVIDEC *Cx* spectroscopic shaping amplifier, which is a low-noise charge amplifier with a rise time of 80 ns and a Gaussian pulse shape with an FWHM of 180 ns. The maximum count rate of the neutron detector

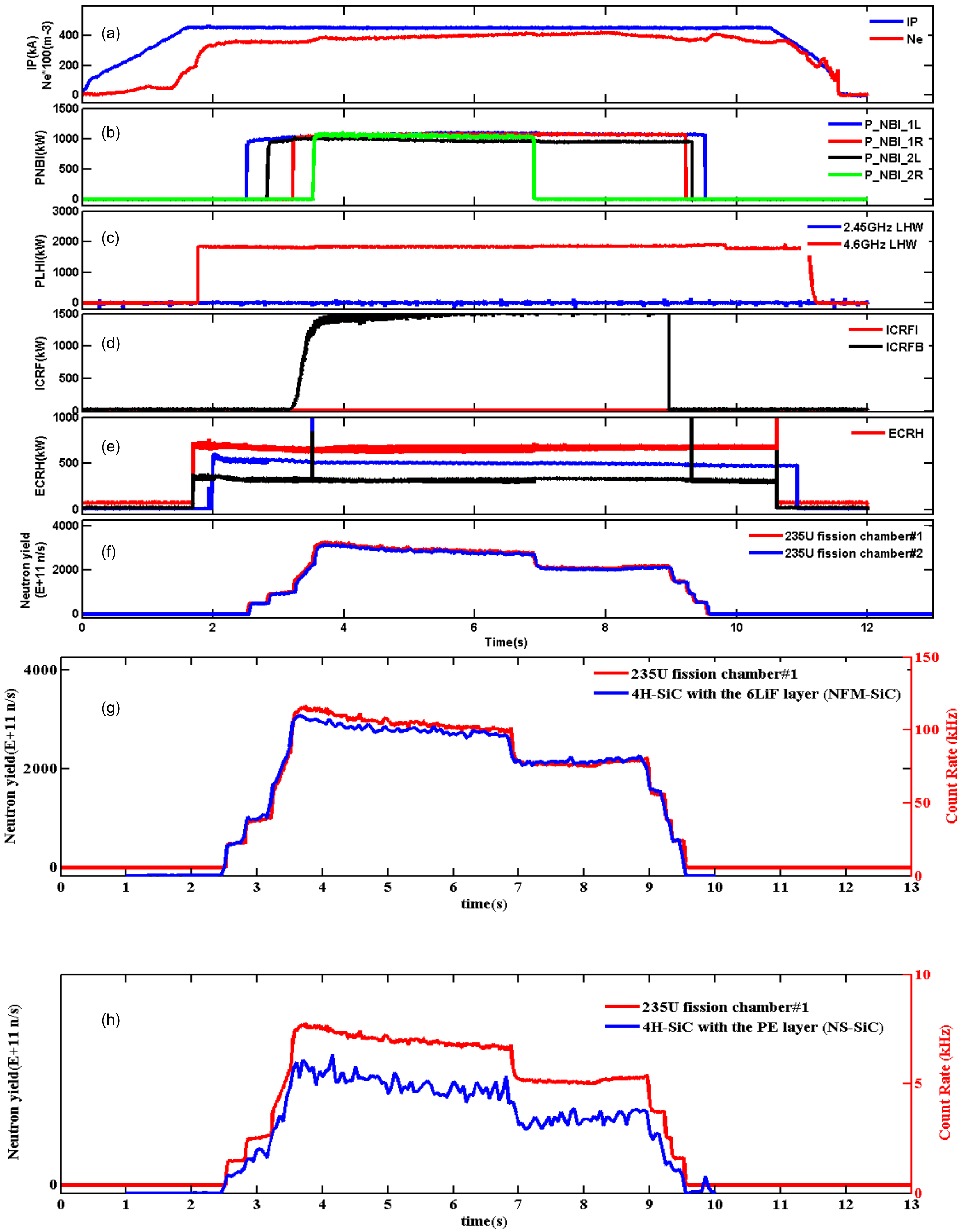

Fig. 5. Shot 101896: (a) plasma current and central line-averaged electron density, (b) **NBI** power, (c) **LHW** power, (d) **ICRF** power, (e) **ECRH** power, (f) the neutron yield measured by the ^{235}U fission chamber, (g) time-dependent neutron emission rate measured with **NS-SiC** (blue Line) and ^{235}U fission chamber#1 (red line), and (h) time-dependent neutron emission rate measured with **NFM-SiC** (blue line), and ^{235}U fission chamber#1 (red line).

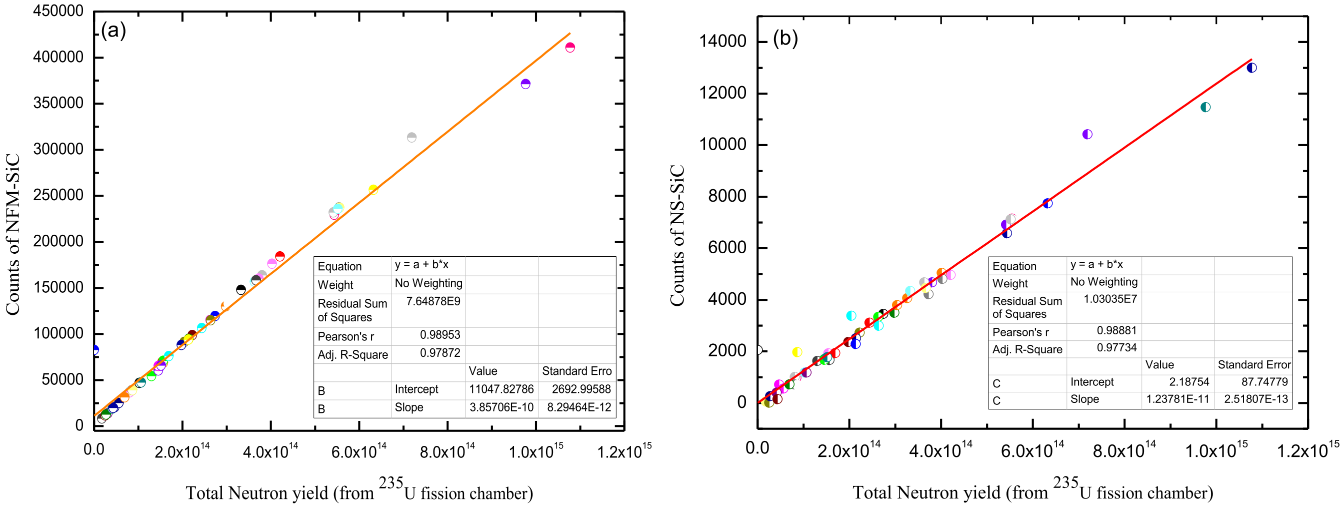

Fig. 6. Counts of **NFM-SiC** and **NS-SiC** detectors and total neutron yield calculated from fission chambers EAST diagnostic in different EAST pulse. (a) NFM-SiC counts vs. total neutron yield, (b) NS-SiC counts vs. total neutron yield.

is about 50 MHz. For the **NS-SiC** detector, the CAEN A1426 fast preamplifier is used, which can shape the signal to 12 ns, that allows working at a rate of few MHz without incurring in signal pile-up. The signals from the fast preamplifiers were then recorded by a 14-bit/500 MHz sampling rate digitizer VXI730, which is manufactured by CAEN, Viareggio, Italy. The digitizer recorded the timestamp and the pulse integral for each event, the information was stored on the PC and the pulse height spectrum was then reconstructed from the stored events. The nominal bias voltage of 4H-SiC detector is -150 V and has been supplied by a CAEN DT1570.

During the 2021 EAST D-D plasma experimental campaigns, the neutron flux monitor and spectrometer based on the 4H-SiC detectors was installed on a viewport located at the mid-plane of port F outside the EAST vacuum vessel. In order to enhance the count rate of neutron event, the 4H-SiC detectors are placed as close to the plasma area as possible, at about 6 m away from the plasma center. During neutral beam injection (**NBI**)-heated plasma operations, neutron fluence at the 4H-SiC detector's location was up to 10^7 n/(cm^2·s). Fig. 3 shows the 4H-SiC detectors installed on the EAST tokamak. The signal of neutron detectors based on the 4H-SiC detector was connected to a computer which was controlled by the internal networking of EAST.

IV. RESULTS AND DISCUSSION

A. Response of 4H-SiC Detector Measurements

Before the 4H-SiC detector was used for measuring the neutron flux and neutron spectrum of EAST device, the energy response of the 4H-SiC detectors for neutron and gamma ray were tested. A 320 MBq ^{137}Cs gamma-ray source was used for gamma-ray irradiation. The ^{137}Cs gamma-ray source was placed approximately 18 cm away from the 4H-SiC detector. For the neutron irradiation, a monochromatic 2.5 MeV neutron produced by D–D compact neutron generator was used and the maximum neutron intensity of this neutron generator is 3×10^8 n/s. The typical neutron signals measured for **NFM-SiC** and **NS-SiC** are shown in Fig. 4. One can notice that the full duration of neutron signal is below 100 ns for **NS-SiC** and below 600 ns for **NFM-SiC**. The deposited energy spectrum was also shown in Fig. 4 that integrates 1800 s of measurement. As can be seen from Fig. 4(c) and (d), the deposited energy induced by the gamma ray in the 4H-SiC detector is mainly concentrated in the low-energy region, mainly because the 4H-SiC detector has a small atomic number, a high ionization energy (7.9 eV), and a thin sensitive layer, and it is difficult for the γ-ray to completely deposit its energy in the sensitive region of the 4H-SiC detector. The high threshold of 100 lsb (least significant bit) for **NFM-SiC** and 50 lsb for **NS-SiC** allows separation of events caused by 2.5 MeV neutrons and gamma ray.

B. Real-Time Neutron Measurement in the EAST

The response of the 4H-SiC detectors has been compared relative to the total neutron yield of EAST measured by ^{235}U fission chambers, both in terms of temporal counts during single plasma pulses and in terms of the total counts versus total neutron yield. The ^{235}U fission chamber, which operate in the pulse mode and Campbell model, is the main neutron diagnostic system used at EAST to measure the time-dependent neutron emission rate produced during single plasma pulses.

For a typical plasma discharge (#101896) with **NBI**, lower hybrid wave (**LHW**), electron cyclotron resonance heating (**ECRH**), and ion cyclotron resonance frequency (**ICRF**) heating system, the plasma current, heating power, the time-dependent neutron counts rate of ^{235}U fission chamber, the neutron flux monitor, and the neutron spectrometer based on the 4H-SiC detectors during plasma discharge are shown in Fig. 5. The total heating power for shot 101896 is about 12 MW and the measurement time resolution of two 4H-SiC detectors and ^{235}U fission ionization chamber is set to 10 ms. It can be seen from Fig. 5 that compared with other heating systems, the neutron flux increases significantly during the application of NBI, because most of the neutrons generated come from the beam target reaction between the fast deuterium ions implanted by NBI and the thermal deuterium ions during plasma discharge.

The absolute efficiency of the ^{235}U fission chamber is calibrated, and thus the neutron yields shown in the figures correspond to the total neutron yields produced during those pulses. Due to not absolute calibration of the 4H-SiC detectors, the measured count rates of the 4H-SiC detectors were shown in Fig. 5. The time-dependent neutron emission rates measured with the neutron monitor flux and neutron spectrometer based on the 4H-SiC detectors in discharges #101896 were compared with that of a ^{235}U fission chamber. Fig. 5(g) and (h) shows the good agreement between the 4H-SiC detectors and the ^{235}U fission chambers, confirming the validity of the neutron flux monitor and neutron spectrometer based on the 4H-SiC detectors. As can be seen from Fig. 4, the count rate of **NFM-SiC** is higher than that of **NS-SiC**. This shows that the detection efficiency of **NFM-SiC** is much higher than that of **NS-SiC**.

The comparison of **NFM-SiC** and **NS-SiC** counts versus the total neutron yield measured with ^{235}U fission chamber for about 60 acquired pulses were shown in Fig. 6. The reported figures point out that the correlation is very strong both at the lowest and at highest neutron yields. The neutron yield measured by the ^{235}U fission chamber is 1×10^{12} to 1×10^{15} n/hot. Among them, the fusion yield under NBI heating is mostly more than 10^{13} n/shot, and the fusion neutron yield is as high as 10^{15} n/shot under high parameter discharge.

V. CONCLUSION

The 4H-SiC detectors with excellent detection/thermal properties are a potential candidate for the semiconductor detector used in thermonuclear fusion. In the 2021 EAST D–D plasma campaign, two 4H-SiC detectors installed in the EATS device demonstrated to be stable and reliable. One 4H-SiC detector covered with the ^{6}Li-enriched LiF layer (named as **NFM-SiC**) was used for measuring the time-dependent neutron emission rate and another 4H-SiC detector covered with the PE layer (named as **NS-SiC**) was used for measuring the D–D fusion neutron energy and the time-dependent neutron emission rate at EAST. The neutron energy spectra and the time-dependent neutron emission rate were successfully recorded from the EAST D–D plasma operations. Two 4H-SiC detectors have been shown to be reliable and complementary to the total neutron yield of EAST diagnostics based on fission chamber detectors. The present results obtained are a useful step toward the optimization of 4H-SiC detector configuration and further studies on the detector performance in the fusion plasma environment on EAST device. For the next EAST campaign, we will study the possibility of using the 4H-SiC as a neutron spectrometer for obtaining information on ion temperature and energy distribution related to interactions with high-energy ions from fast ion measurements and neutron emissivity of 14 MeV. In conclusion, the 4H-SiC detectors are expected to play an important role in burning plasma diagnostics in fusion plasmas on EAST as well as in next step devices, such as CFETR and ITER.

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