

CONFERENCE PRE-PRINT**IN-SITU CALIBRATION OF NEUTRON FLUX MONITOR FOR HL-3 TOKAMAK**

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Abstract

In-situ calibration is essential for neutron flux systems. The paper describes the process and results of rapid in-situ calibration performed on the HL-3 tokamak. The calibrated neutron source was Cf-252 with an intensity of 6.71×10^6 n/s. Calibration was performed at 33 distinct points along the magnetic axis. The calibration process, including setup and dismantling of the neutron source control system, took 14 hours. Subsequently, cross-calibration of the detector's Campbell model was performed using the plasma neutron source. Results demonstrate the system's measurement range spans from 10^{10} n/s to 10^{17} n/s.

1. INTRODUCTION

Neutron flux monitors, as fusion power measurement systems are important for ITER and future fusion reactors because the ultimate goal of fusion research is to output fusion power. The neutron flux monitor then needs to be calibrated in-situ in order to obtain the fusion power from the measurements. Calibrated neutron sources are of limited strength and have different energy properties and spatial distributions than plasma sources. Therefore, in-situ calibration is a very complex task. Lots of effort and time went into the in-situ calibration at many devices[1, 2]. Machine time for future fusion devices is very valuable. It is very attractive to reduce the use of machine hours and to perform in-situ calibrations efficiently. In January 2025, a total of 14 hours of rapid in-situ calibration was conducted on the HL-3 Tokamak (formerly HL-2M) [3] device. Section 2 describes the calibration process, Section 3 presents the calibration results and experimental findings, followed by a conclusion and discussion.

2. IN-SITU CALIBRATION

The Neutron Flux Diagnostics consists of five B-10 counters for low neutron flux measurements, and 4 U-235 fission chamber detectors, arranged as shown in shown in Fig. 1. The B-10 counter has a sensitivity of about 3 cps/nv, was placed in 5-cm polyethylene moderator. Additionally, a 2 cm lead layer is positioned between the detector and the polyethylene to further attenuate gamma rays' interference[4]. Two high sensitivity fission chambers (No. 1 and 2) are about 1~2 g U-235, two other low sensitivity fission chambers (No. 4 and 5) are about 0.1 g U-235. All fission chambers were placed in a 5-cm polyethylene moderator.

The neutron source used for the calibration was the Cf-252 neutron source with an intensity of about 6.71×10^6 n/s on the calibration date. The source is encapsulated in a stainless steel housing with a diameter of 8 mm and a length of 40 mm.

The neutron source positioning structure consists of an aluminum-plastic pipe with an 8-millimeter rope inside, along with the neutron source container. The pipe is approximately 15 meters long, with an outside diameter of 32 mm and an inside diameter of 26 mm. Every meter, a marker is tied to the rope. The neutron source container is manufactured via 3D printing. Both ends of the container feature rings for rope attachment. The procedure for threading a rope through an aluminum-plastic pipe is as follows: Attach one end of the rope to a magnet and insert it into the pipe. Using another magnet outside the pipe, pull the magnet inside the pipe to the opposite end. Then, the engineers pulled the pipe into the vacuum chamber through the window between the toroidal field coils #18 and #19. During the pull-in process, the engineers manually bent the pipe gradually to bring it closer to the magnetic axis position. The pipe was then secured to bolts inside the vacuum chamber by means of ropes. Based on the measurement results, the engineers adjusted the tension of the rope to ensure the precise position of the pipe. The neutron source container was tethered to a rope without loading the neutron source and pulled to traverse

the entire length of the pipeline. The total length of the circuit was measured to be approximately 11 meters. For measurement convenience, 33 calibration points were established, equating to three calibration points per meter. Since the inlet and outlet sections deviated from the magnetic axis, the calibration start and end points were set near the end of the inlet section and the beginning of the outlet section, respectively. The inlet section was then cut to facilitate source insertion. The outlet section retained sufficient length to match the rope markings, with the remaining portion removed. A schematic diagram of the neutron source positioning structure is shown in Fig. 1. The whole installation process took about 2.5 hours. Dismantling after calibration took 1 hour.

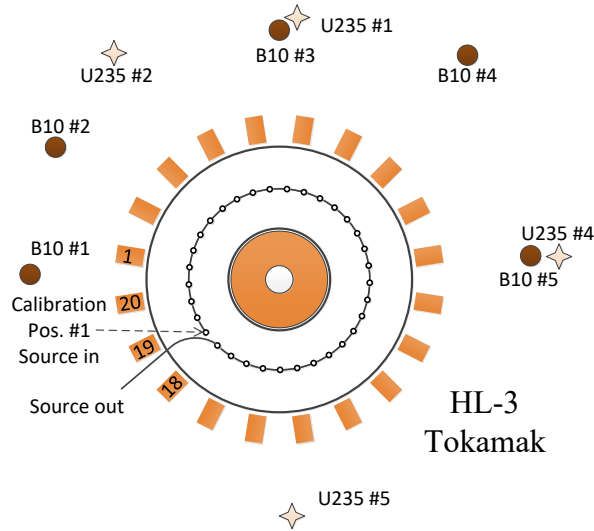


FIG. 1. Detector arrangement of the HL-3 neutron flux monitor, and schematic diagram of the calibration structure and distribution of calibration points

The neutron source was placed into the neutron source container, transported to the calibration point, and all neutron detectors were activated for a 20-minute measurement. Including the time required to move the neutron source, the entire calibration process lasted 10.5 hours. The calibration work was conducted during the night.

The neutron source intensity was insufficient to achieve the Campbell operating mode in the U-235 fission chamber. A low-power neutron beam heating discharge was selected for Campbell mode calibration. See the next section for details.

3. CALIBRATION AND EXPERIMENTAL RESULTS

Prior to calibration, the background counts for all detectors were obtained through 12 hours of continuous measurement. Subtracting the detector background, the response at different locations considering statistical errors are shown in Fig. 2. The errors in most of the results are not significant, except for 3 points of the low-sensitivity U-235 fission chamber. The detection efficiencies of the detectors were obtained by averaging, with the B-10 counting tubes and the high-sensitivity U-235 fission chambers having a detection efficiency error of less than 1%, and the rest of the detectors at about 3%, as shown in Table 1.

TABLE 1. Calibration results for detector efficiency

Detector	Efficiency	Statistical error
B-10 #1	2.30×10^{-7}	0.5%
B-10 #2	1.82×10^{-7}	0.5%
B-10 #3	3.05×10^{-7}	0.4%
B-10 #4	5.09×10^{-8}	1.0%
B-10 #5	7.62×10^{-8}	0.8%
U-235 #1	1.13×10^{-7}	0.7%
U-235 #2	1.97×10^{-7}	0.5%
U-235 #4	5.69×10^{-9}	3.6%

U-235 #5

 1.21×10^{-8}

2.5%

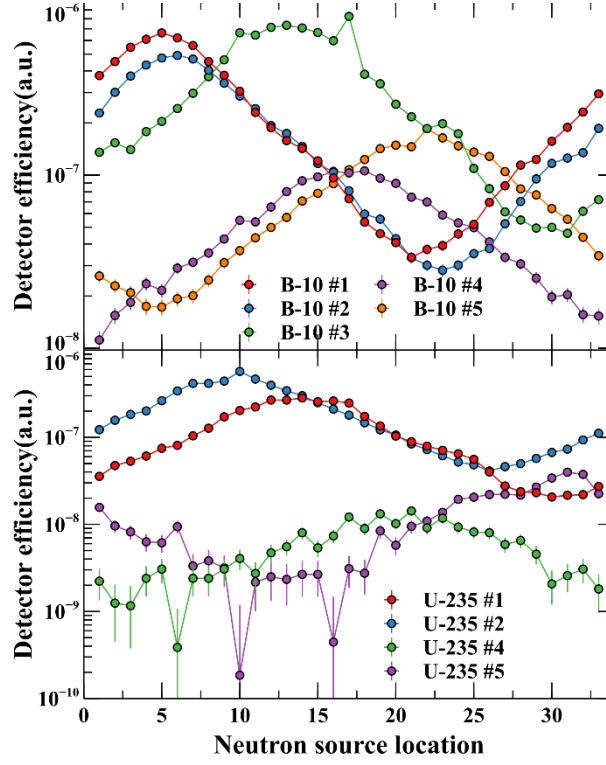


FIG. 2. In-situ calibration results for detector efficiency.

Considering a total uncertainty of 20% with a statistical uncertainty of 15%, and a time resolution of 10 ms, the detector count rate should exceed 4.5 kcps. The maximum count rates for the B-10 proportional counter and the U-235 fission chamber are 30 kcps and 500 kcps, respectively. The Campbell model U-235 fission chamber achieves a maximum count rate of 1 Gcps. Then the calibration results show that the most sensitive neutron detector can cover measurements up to 1×10^{10} n/s, and the least sensitive neutron detector can cover measurements up to 1.7×10^{17} n/s if the maximum count rate reaches 1×10^9 Hz, as shown in Fig. 3.

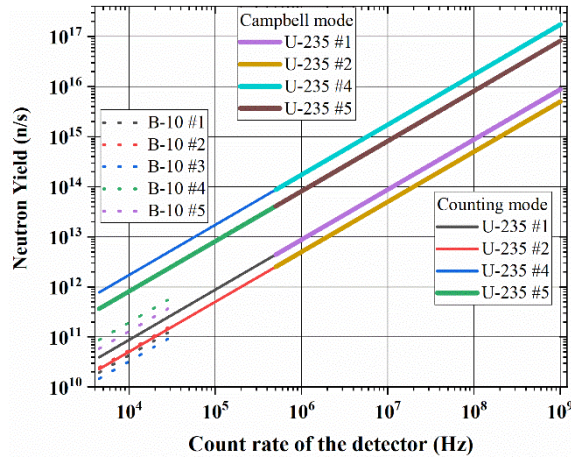


FIG. 3. Measuring range of the detector.

Fig. 4(a) depicts a typical ohmic discharge with key parameters: deuterium plasma current ~ 1 MA, core electron density about $\sim 3 \times 10^{19}/\text{m}^3$ [5], electron cyclotron heating (ECH) of ~ 1.5 MW. Fig. 4(b) presents the neutron

production rate results, obtained by weighting the measurements from five B-10 proportional counters. The weighting coefficients were selected to minimize statistical uncertainty, as detailed in Chapter 3 of Ref.[6]. The time resolution of neutron production rate is 10 ms. Fig. 4(c) to (g) show the residuals from five B-10 proportional counter tubes. All residuals are distributed on both positive and negative sides, with no apparent systematic bias. This indicates that the arrangement and design of the B-10 proportional counter tube render it insensitive to differences between calibration sources and plasma sources. However, due to its low maximum count, the B-10 has a limited measuring range and serves primarily to indicate neutron production.

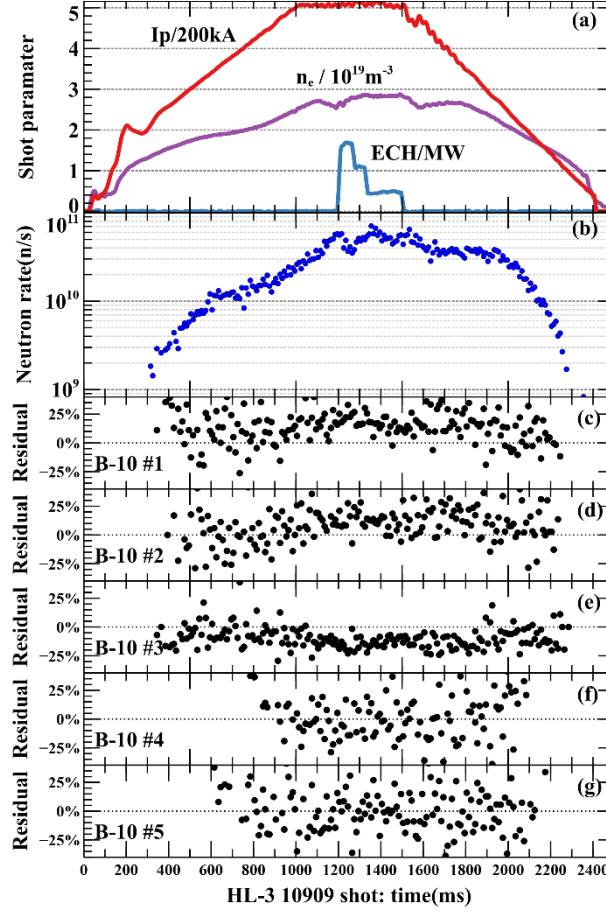


FIG. 4. HL-3 10909 shot parameter.

Fig. 5(a) shows a plasma heated by a neutral beam, with key parameters: deuterium plasma current ~ 500 kA, core electron density of $\sim 1.5 \times 10^{19}/\text{m}^3$, neutral beam heating power of ~ 1.1 MW. Fig. 5(b) presents the neutron production rate results, obtained by weighting the measurements from two U-235 fission chamber(#4 and #5). The time resolution of neutron production rate is 10 ms. Fig. 5(c) and (d) show the residuals from two U-235 fission chamber. All residuals are distributed on both positive and negative sides, with no apparent systematic bias.

The maximum neutron production rate exceeded 10^{13} neutrons/s. According to Fig. 3, U-235 fission chambers #1 and #2 will enter the Campbell mode. The Campbell mode for U-235 #1 and #2 was cross-calibrated using results from U-235 #4 and #5, as shown in Fig. 6. According to literature, signal variance is proportional to neutron flux; however, noise and background effects degrade this relationship to a linear correlation. In the fitting process, the intercept is set to the opposite value of the observed quantity under the neutron-free condition. Nevertheless, results from intercept sensitivity analysis indicate that intercept setting affects slope fitting outcomes by less than 2%. The cross-calibration results for U-235 #1 and 2 are listed in Table 2.

TABLE 2. Cross-calibration results for U-235 #1 and 2

Detector	Intercept (mV^2)	Slope ($10^{-10} \text{mV}^2/(\text{n/s})$)
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U-235 #1	-35.52	9.39
U-235 #2	-24.83	5.31

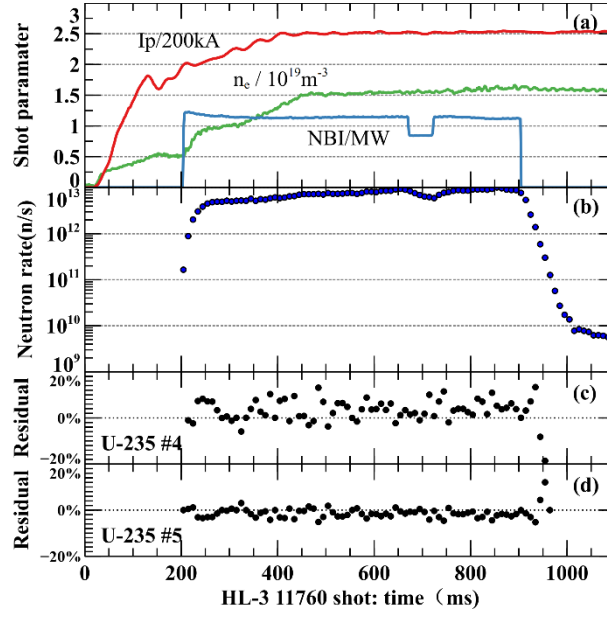


FIG. 5. HL-3 11760 shot parameter.

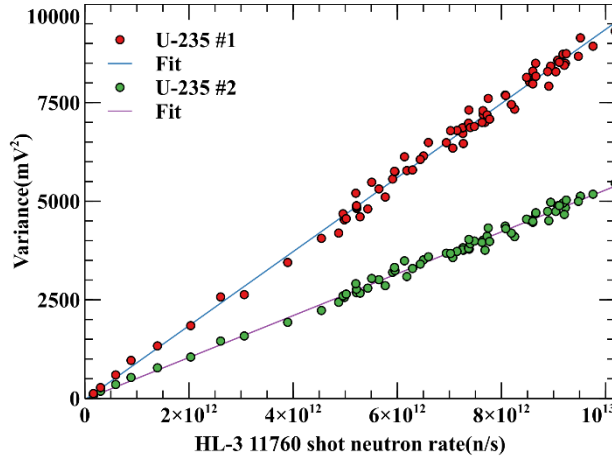


FIG. 6. Cross-calibration of the Campbell model using a plasma neutron source.

Fig. 7(a) shows a plasma heated by a neutral beam, with key parameters: deuterium plasma current ~ 1.03 MA, core electron density of $\sim 2.6 \times 10^{19} \text{ m}^{-3}$, neutral beam heating power of ~ 2.8 MW. Fig. 7(b) displays all neutron production rate results measured by the B-10 proportional counter tube, the counting results from U-235 fission chambers #4 and #5, and the Campbell model weighted average for U-235 fission chambers #1 and #2. The B-10 results saturated at approximately 10^{12} n/s. Counting in the U-235 fission chamber exhibited loss of counts beyond 2×10^{12} n/s due to pulse pile-up. These findings are consistent with the predictions in Fig. 3. The neutron production rate has a time resolution of 10 ms. The time resolution of the neutron production rate is 10 ms. Fig. 7(c) and (d) show the residuals from two U-235 fission chamber. All residuals are distributed on both positive and negative sides, with no apparent systematic bias.

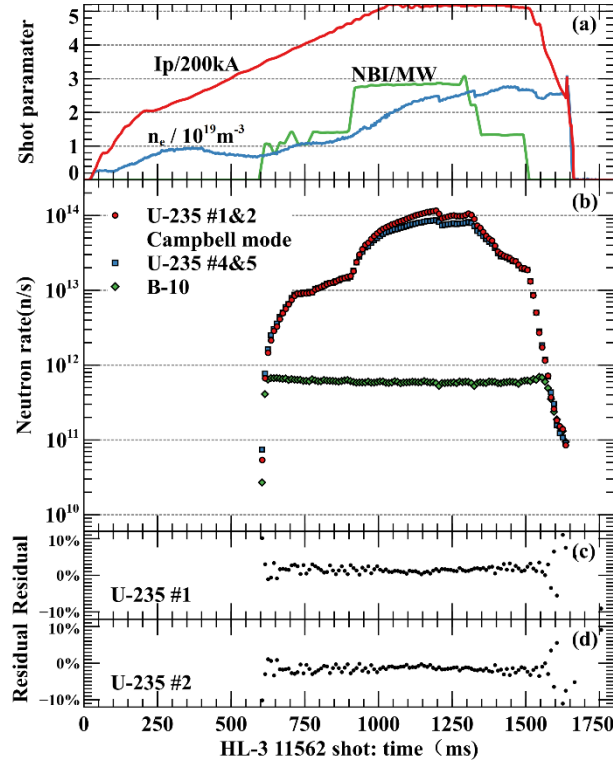


Fig. 7. HL-3 11562 shot parameter.

4. CONCLUSIONS AND DISCUSSION

Using a Cf-252 neutron source with an intensity of 6.71×10^6 n/s, we completed the calibration of the counting mode for the neutron flux measurement system in the HL-3 tokamak in less than one day. Subsequently, the highly sensitive U-235 Campbell model was cross-calibrated using plasma discharges. With a 10 ms time resolution and 20% uncertainty, the system's measurement range spans from 1×10^{10} n/s to 1.7×10^{17} n/s.

For the ITER neutron measurement system with a range of 1×10^{14} n/s to 2×10^{20} n/s, the maximum measurement range is three orders of magnitude higher than that of the HL-3 system. If a neutron source with an intensity of 6.71×10^9 n/s is used, small neutron generators of this intensity exist, the two are closer in terms of calibration difficulty and complexity, and the calibration time required is similar. Based on the above comparative analysis, this similarity suggests that our low-range calibration experience is still of some reference value despite the higher measurement range and system complexity of ITER. By learning from our calibration strategy, time planning, and resource allocation methods, the calibration process of the ITER neutron measurement system is expected to be optimized to improve efficiency and reduce potential uncertainties.

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