Dynamic Linear Calibration Method for a Wide Range Neutron Flux Monitor System in ITER (Postprint)

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Date: 2023-06-18T00:00:00+00:00

Abstract

As a key part of the diagnosis system in the International Thermonuclear Experimental Reactor (ITER), the neutron flux monitor (NFM), which measures the neutron intensity of the fusion reaction, is a Counting-Campbelling system with a large dynamic counting range. A dynamic linear calibration method is proposed in this paper to solve the problem of cross-over between the different counting and Campbelling channels, and improve the accuracy of the cross-calibration for long-term operation. The experimental results show that the NFM system with the dynamic linear calibration system can obtain the neutron flux of the fusion reactor in real time and realize the seamless measurement area connection between the two channels.

Full Text

Preamble

Dynamic Linear Calibration Method for a Wide-Range Neutron Flux Monitor System in ITER

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Abstract

As a key diagnostic component of the International Thermonuclear Experimental Reactor (ITER), the neutron flux monitor (NFM) measures neutron intensity from fusion reactions using a Counting-Campbelling system with a large dynamic range. This paper proposes a dynamic linear calibration method to solve the cross-over problem between different counting and Campbelling channels and improve the accuracy of cross-calibration for long-term operation. Experimental results demonstrate that the NFM system with dynamic linear calibration can obtain real-time neutron flux from the fusion reactor and achieve seamless measurement range connection between the two channels.

Keywords: Dynamic linear calibration, Long-term stability, Cross-over, Neutron flux monitor, International Thermonuclear Experimental Reactor (ITER)

Introduction

As a critical diagnostic system in the International Thermonuclear Experimental Reactor (ITER), the neutron flux monitor (NFM) provides real-time measurements of global neutron source intensity, fusion power, and neutron flux [**?**]. To extend the measurable range of neutron flux, the NFM can operate in three distinct modes: pulse mode for count rates below 10^6 counts per second (cps), Campbelling mode (also known as “fluctuation mode” or “mean square voltage mode”) for count rates above 10^5 cps, and current mode for even higher counting rates \cite{2–4}. Accurate calibration of both counting and Campbelling modes is essential for precise neutron flux determination, with good cross-over between the two modes being equally important. The counting mode is calibrated through detection efficiency calibration of fission chambers [**?**, **?**], while the Campbelling mode is subsequently calibrated based on single neutron pulse charge measurements.

It is impractical to calibrate the absolute efficiency for all fission chamber types with varying sensitivities in the NFM system. Experimental methods can only calibrate the most sensitive fission chambers [**?**], which are then used as empirical references to calibrate others [**?**]. Studies on single neutron pulse charge calibration in Campbelling mode indicate that calibration in a neutron environment is similar to that performed by the detector itself [**?**]. However, providing such a neutron environment is challenging, as ITER represents one of the largest controllable nuclear fusion reactors under construction.

The absolute measurement uncertainty of the total fusion neutron yield for the NFM must be less than 10% [**?**], a requirement that previous cross-calibration methods struggle to meet. For instance, cross-calibration uncertainty in the Tokamak Fusion Test Reactor (TFTR) could reach 10% [**?**]. For long-term operation, aging effects in NFM components—including the fission chamber, preamplifier, main amplifier, and Campbelling Integrator—must be evaluated. Environmental temperature and heat generated by electronic devices cannot be ignored, as the NFM can reach temperatures of 300°C [**?**]. Consequently, cross-calibration for the Campbelling mode in the NFM remains an active research area.

In designing the wide-range Counting-Campbelling NFM system, the Dynamic

Linear Calibration (DLC) method was proposed to calibrate the Campbelling mode and eliminate cross-calibration influences on measurement accuracy. The counting mode operates in the range of 0–10^6 cps, while the Campbelling mode covers 10^4–10^8 cps.

2. Design of the Wide-Range NFM System

The system must provide a dynamic range of 10^8 cps, a time resolution of 1 ms, and measurement uncertainty of less than 10% for absolute neutron flux determination. The designed framework of the NFM system is shown in [Figure 1: see original paper], with the field experiment setup depicted in [Figure 2: see original paper]. The NFM comprises two fission chambers with different sensitivities and an additional "blank" chamber. The blank chamber contains no fissile material but has identical dimensions to the fission chambers, enabling identification of background radiation such as gamma rays [**?**].

The most challenging aspect of the NFM system is eliminating α and γ rays and other noise radiation accompanying neutrons in thermonuclear fusion reactions [**?**, **?**]. Pulse shape discrimination technology is typically employed to distinguish neutrons from gammas [**?**]. The n–γ Pulse Shape Discriminator (n–γ PSD) is designed for a measurement range of 0–10^6 cps where minimal pulse pileup occurs. It extracts the rise time and amplitude of each pulse to determine whether it originates from a neutron or gamma event, transmitting only neutron pulses to the Time Division Scaler unit for processing. Thus, the count rate from the scaler unit represents the pure neutron flux.

The Campbell Integrator, which integrates the input signal, is designed for the measurement range of 10^4–10^8 cps where pulse pileup must be considered [**?**]. Based on Campbell's theorem, the analog voltage output from the Integrator is proportional to neutron flux [**?**]. This output voltage is sent to the Waveform Recording unit for processing.

The outputs from both the Time Division Scaler unit and the Waveform Recording unit, representing real-time neutron flux, are transmitted to the Centralized Control module, which forwards the results to local software. The software transfers neutron flux data to the CODAC system online at intervals no longer than 1 ms for real-time feedback control.

3. DLC Method

The output voltage from the Campbelling channel must be converted to neutron counts. The primary challenge is that providing a neutron environment similar to ITER for fission chamber calibration in Campbelling mode is difficult, and the Campbelling channel output voltage is significantly affected by numerous factors including electronic device baseline shifts, temperature drift, and aging of both electronic devices and the fission chamber. These issues are unavoidable during long-term operation, motivating the development of the DLC method.

Two points are selected within the overlapping measurement range of 10^4–10^6 cps between the counting and Campbelling channels. The outputs from both channels at these two points are obtained and fitted using a linear equation as follows:

$$F_{\text{neutron}} = A \times V_{\text{amp}} + B$$

where F_{neutron} represents the output from the counting channel (true input neutron flux) and V_{amp} is the voltage from the Campbelling channel. This equation describes the relationship between input neutron flux and Campbelling channel output within the 10^4–10^6 cps range. Since the Campbelling channel is a linear system, its analog output can be converted to neutron flux across the full 10^4–10^8 cps range.

The DLC method is straightforward to implement and can be performed dynamically during experiments. When neutron flux during an experiment falls within the overlapping measurement range of 10^4–10^6 cps, two or more points can be selected automatically or manually via software. The software can select the appropriate channel based on neutron flux level, and the correction coefficients A and B can be applied immediately or stored for subsequent experiments.

The proportional coefficient $N = 6.25 \times 10^4$ relates DC voltage levels to neutron pulse frequency, enabling conversion of input DC voltage to pulse frequency from 6.25×10^5 cps to 1.25×10^8 cps. The input pulse frequency range in [Figure 4: see original paper] spans 10^4 cps to 3×10^6 cps. Integrating these two input pulse frequency ranges yields Curve 2 in [Figure 6: see original paper], which shows the relationship between input signal frequency and Campbell Integrator output voltage. A controllable signal attenuator is employed in the Campbell Integrator, and the output voltage in Curve 2 represents the product of the attenuation ratio and the actual Integrator device output.

The DLC method eliminates the need to find a neutron environment similar to ITER for fission chamber calibration in Campbelling mode and enhances system adaptability to various long-term environmental conditions. Coefficient A eliminates baseline drift and device aging effects, while coefficient B significantly improves the ability to adjust amplifier gain, which typically varies with temperature and device aging. This substantially improves experimental accuracy.

4. Tests and Results

Field experiment data reveal typical neutron pulse parameters: rise time $T_r = 80$ ns, fall time $T_f = 160$ ns, full width at half maximum (FWHM) = 160 ns, and amplitude $V_i = 100$ mV. This signal was simulated using a signal generator in the laboratory to test the NFM system.

First, the n–γ PSD and Campbell Integrator were tested using the signal generator output. Results are shown in [Figure 3: see original paper] and [Figure

4: see original paper]. The F_{neutron} output from the n–γ PSD equals the input pulse frequency when the input frequency is below 3 MHz.

A DC level represents the piled-up neutron pulse signal. The DC voltage sent to the Campbell Integrator was varied from 10 mV to 2000 mV, with test results shown in [Figure 5: see original paper].

The area of one simulated neutron pulse is $S_1 = \text{FWHM} \times V_i = 1.6 \times 10^{-8}$ Vs. The area of a 1 mV DC level over 1 s is $S_2 = 1 \text{ mV} \times 1 \text{ s} = 0.001$ Vs. The proportional coefficient $N = S_2/S_1 = 6.25 \times 10^4$, meaning a 1 mV DC level signal has the same area as 6.25×10^4 neutron pulses in 1 s.

Two points, P_1 (500 kHz, 380 mV) and P_2 (1000 kHz, 780 mV), are selected from [Figure 6: see original paper]. Fitting using Eq.(1) yields $A = 25,000$ and $B = 1,250$, enabling conversion of Campbell Integrator output voltage to neutron flux. As shown in [Figure 7: see original paper], the NFM system achieves a linear dynamic range of 1.25×10^8 cps with a linear correlation coefficient of 0.99995, effectively solving the cross-over between the two channels.

5. Conclusion

To measure neutron flux across the 0–10^8 cps range, a counting-Campbelling system has been designed. The developed DLC method readily solves the cross-over problem between counting and Campbelling channels. By improving the ability to eliminate baseline drift, temperature variation, and device aging effects, the DLC method enhances cross-calibration accuracy and makes the system more adaptable to diverse environments. The ITER NFM system has passed laboratory tests using simulated neutron signals, and joint testing has been conducted in a steady neutron radiation field using a fission chamber and preamplifier. Experimental results demonstrate that the NFM system has achieved its anticipated goals.

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