

Determination of the Optimal Duty Cycle of a Pulsed Neutron Generator Based on Decay Time Analysis of DDA Signals

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1. Introduction

The Differential Die-Away (DDA) method detects nuclear material by supplying neutrons from a pulsed neutron generator, interrupting the beam, and measuring the neutrons produced by induced fission during the beam-off period [1,2]. Since the quantity of interest appears only after the beam is switched off, the duty cycle and the on time of the generator directly govern the quality of the measurement [3].

Two competing constraints limit the choice of on time. If it is too short, the rise behavior of the generator occupies a significant fraction of the pulse and the extracted decay time becomes unstable. If it is too long relative to the pulse period, the signal has not decayed sufficiently before the next pulse injects new neutrons, introducing an error into the decay time. The operating point must therefore lie where the decay time is independent of the on time, while leaving a die-away interval long enough to determine that decay time reliably. In this work, DDA signals were measured at several duty cycles with the pulse period fixed, the die-away region was fitted with a two-component exponential model, and the duty cycle range over which the decay times remain independent of the operating condition was identified.

2. Methods and Results

2.1 Experimental Setup

The neutron source was a DD108 generator (Adelphi Technology Inc., USA) with a maximum output of 1×10^8 n/s, producing 2.45 MeV neutrons via the D-D fusion reaction. Neutrons were measured with twelve ³He proportional counters (LND Inc., USA), each with an active length of 50 cm and a diameter of 2.54 cm, filled with ³He at 4 atm. The array was enclosed by a 0.6 wt% borated polyethylene.

Signals were processed with a preamplifier and a Flash ADC (Notice Co., Korea), and a Trigger Control Board recorded the TTL trigger from the generator microwave as the time reference. After moving-average and CR-RC⁴ filtering, valid neutron peaks were synchronized to the trigger points to construct the time-dependent DDA signal, using a 1 μ s time bin and the aggregated signal of

all twelve counters. The pulse period was fixed at 1 ms, and the duty cycle was first varied over 20 %, 40 %, 60 % and 80 %, each measured for 5 minutes.

2.2 Decay Time Model

The die-away region is not described by a single exponential: the fast and thermal neutron components decay on distinctly different time scales, as shown in Fig. 1 together with an MCNP6 simulation of the same geometry. The region was therefore fitted with Eq. (1):

$$N(t) = A_1 e^{-\frac{t-t_0}{\tau_f}} + A_2 e^{-\frac{t-t_0}{\tau_{th}}} + C \quad (1)$$

where t_0 is the time at which neutron emission ends, τ_f and τ_{th} are the fast and thermal decay times, and A_1 , A_2 and C are fitting coefficients. Equation (1) was solved by nonlinear least squares using the least squares function of SciPy, with the fitting interval extending from the end of the beam pulse to the end of the period. Agreement between data and fit was quantified by the mean absolute percentage error (MAPE).

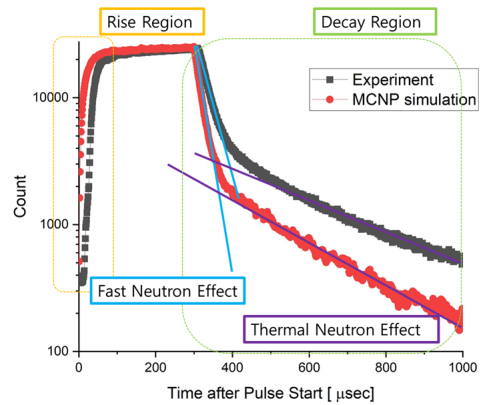


Fig. 1. Rise and decay regions of the DDA signal, showing the fast and thermal neutron contributions to the die-away interval (experiment vs. MCNP6 simulation).

2.3 Decay Time as a Function of Duty Cycle

Table I: Decay Times as a function of duty cycle

Duty Cycle [%]	Fitting Range [μs]	τ_f [μs]	τ_{th} [μs]	MAPE [%]
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20	201 – 1000	26.09	523.05	6.85
40	401 – 1000	25.87	535.93	3.96
60	601 – 1000	27.57	45508.37	2.91
80	801 – 1000	29.47	6207.25	3.51

Fig. 2 shows the measured data and fitted curves, and Table I the extracted decay times. The MAPE at 20 % was the largest, at 6.85 %, reflecting the poorer counting statistics of the short on time.

τ_f showed no large variation over the range examined. τ_{th} , however, changed drastically at 60 % and above, returning values far longer than the pulse period (1 ms) itself. At these duty cycles the fitting interval is 400 μ s or less, which cannot constrain a slow decay component, so the second exponential term is no longer determined by the data. Duty cycles of 60 % and above were therefore judged unsuitable.

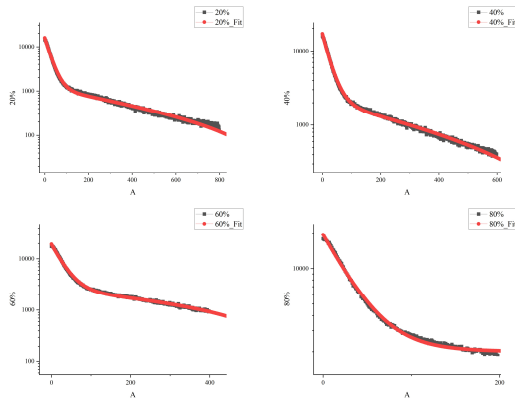


Fig. 2. Measured data and fitted curves for duty cycles of 20%, 40%, 60%, and 80%

2.4 Validation over the 20 – 40% Range

Additional measurements were carried out in 5 % steps between 20 % and 40 %, and a Z-score was calculated as $Z = |\tau - \bar{\tau}|/\sigma$, where $\bar{\tau}$ and σ are the mean and standard deviation of the decay times over the range.

Table II: Consistency over the 20 – 40 % duty cycle range

Duty Cycle [%]	Fitting Range [μ s]	τ_f [μ s]	Z (τ_f)	τ_{th} [μ s]	Z (τ_{th})	MAPE [%]
20	201 – 1000	26.09	0.496	523.05	0.751	6.85
25	251 – 1000	26.84	1.026	611.58	1.106	6.84
30	301 – 1000	25.98	0.719	514.52	0.930	5.11
35	351 – 1000	26.89	1.135	609.22	1.057	4.94
40	401 – 1000	25.87	0.946	535.93	0.481	3.96

The corresponding data and fits are shown in Fig. 3. Over this range the Z-scores of both τ_f and τ_{th} did not exceed 1.14, and neither quantity showed a systematic trend with duty cycle, so no single condition is separated as an outlier. The decay times were therefore taken to be

independent of duty cycle between 20 % and 40 %, and the mid-point of the range, 30 %, was adopted as the baseline operating condition.

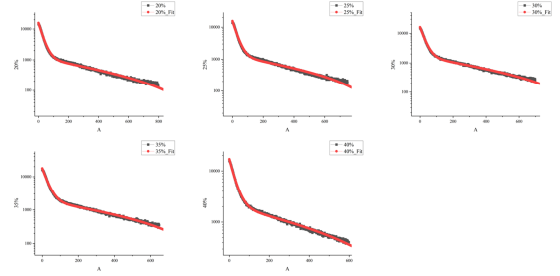


Fig. 3. Measured data and fitted curves for duty cycles of 20%, 25%, 30%, 35%, and 40%.

3. Conclusions

The die-away region of the DDA signal was fitted with a two-component exponential model, and the extracted decay times were examined as a function of duty cycle at a fixed pulse period of 1 ms.

At 60 % and above, the remaining die-away interval is too short to determine the thermal component and τ_{th} deviated by more than an order of magnitude, making this range unsuitable. Between 20 % and 40 %, both τ_f and τ_{th} stayed within a Z-score of 1.14 with no systematic dependence on duty cycle. A duty cycle of 30 % was selected as the baseline condition, retaining a sufficient die-away interval while avoiding the degraded counting statistics seen at 20 %.

Because the extracted decay times depend on how realistically the emission pulse is represented, future work will combine this criterion with a reconstructed emission pulse and extend the verification to other pulse periods.

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REFERENCES

- [1] IAEA, Compact Accelerator Based Neutron Sources, 1st ed., International Atomic Energy Agency, 2021.
- [2] R. Remetti, G. Gandolfo, L. Lepore, N. Cherubini, In field application of differential die-away time technique for detecting gram quantities of fissile materials, Nucl. Instrum. Methods Phys. Res. A, Vol.870, pp.123-130, 2017.
- [3] M. T. Swinhoe, A. Goodsell, K. D. Ianakiev, M. Iliev, D. J. Desimone, C. D. Rael, V. Henzl, P. J. Polk, Development of Techniques for Spent Fuel Assay – Differential Dieaway Final Report, LA-UR-16-25686, Los Alamos National Laboratory, 2016.