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Fiber Bragg Grating–Based In-Core Neutron Flux Monitoring with Bias- and Gain-Aware State Estimation in a 13-String Boiling Water Reactors Configuration: A Short Communication

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Abstract: Accurate three-dimensional reconstruction of neutron flux in Boiling Water Reactors (BWRs) is critical for safe power operation and thermal margin management. Conventional in-core instrumentation provides limited spatial coverage and is subject to calibration drift, bias, and gain uncertainties that degrade long-term accuracy. This work presents an Ensemble Kalman Filter (EnKF)-based framework for real-time flux estimation in a 13-string × 24-axial-node BWR configuration, integrating flux and gamma thermometer measurements within a void-coupled core dynamics model. The proposed method augments the state vector with adaptive bias and gains parameters for each instrument string, enabling simultaneous core state reconstruction and online sensor self-calibration. Simulation results demonstrate improved flux reconstruction accuracy, reduced measurement residuals, and robust tracking of sensor drift under transient operating conditions. The approach provides a foundation for next-generation digital twin architectures and fiber-optic–based in-core monitoring systems for advanced BWR.

Keywords: Nuclear Engineering Boiling Water Reactor (BWR), Fiber Bragg Grating (FBG) Sensors, Ensemble Kalman Filter (EnKF).

1. Introduction

Accurate real-time reconstruction of the three-dimensional neutron flux distribution in Boiling Water Reactors (BWRs) is essential for safe operation, thermal margin management, and power maneuvering. Conventional in-core instrumentation, such as Local Power Range Monitors (LPRMs) and Gamma Thermometers (GTs), provides valuable but spatially limited measurements and is susceptible to calibration drift, bias, and gain variations over extended operation. The increasing interest in fiber-optic sensing technologies, particularly Fiber Bragg Grating (FBG)-based systems, offers new opportunities for distributed, radiation-tolerant flux and temperature monitoring within reactor cores.

However, integrating heterogeneous sensor data into a physically consistent core model requires advanced state estimation techniques capable of handling nonlinear void–moderation feedback and sensor uncertainties. In this work, an Ensemble Kalman Filter (EnKF) framework is developed for three-dimensional neutron flux reconstruction in a 13-string × 24-axial-node BWR configuration. The proposed method explicitly incorporates adaptive bias and gains states for both flux and temperature measurements, enabling real-time correction of sensor drift while preserving physically consistent void-coupled flux dynamics.

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2. What Is a Fiber Bragg Grating (FBG)?

A Fiber Bragg Grating (FBG) is a periodic modulation of refractive index written into the core of an optical fiber. See Fig. 1 and Fig. 2.

It acts as a wavelength-selective mirror.

The Bragg condition:

$$\lambda_B = 2n_{\text{eff}}\Lambda$$

Where:

- λ_B = reflected (Bragg) wavelength.
- n_{eff} = effective refractive index.
- Λ = grating period.

Any change in:

- Strain.
- Temperature.
- Pressure.
- radiation damage.

→ changes n_{eff} or Λ

→ shifts the reflected wavelength.

That wavelength shift is what we measure.

3. How Can FBGs Detect Neutron Flux?

An FBG does not directly detect neutrons electrically like an SPND or fission chamber.

Instead, it measures secondary physical effects caused by neutron interactions.

There are three primary physics mechanisms:

3.1 Mechanism 1: Radiation-Induced Refractive Index Change (RIRIC)

Neutron radiation causes:

- Atomic displacement damage.
- Creation of color centers in silica.
- Compaction of the glass matrix.

These changes:

$$n_{\text{eff}} \rightarrow n_{\text{eff}} + \Delta n_{\text{rad}}$$

Result:

$$\Delta\lambda_B = 2\Lambda\Delta n_{\text{rad}}$$

The magnitude of refractive index changes correlates with:

- Neutron fluence.
- Neutron flux × time.
- Energy spectrum.

This allows integrated neutron dose measurement.

3.2 Mechanism 2: Radiation-Induced Swelling/Strain

Neutron interactions cause:

- Lattice displacement.
- Volumetric compaction or swelling.
- Structural relaxation.

This changes the grating spacing:

$$\Lambda \rightarrow \Lambda + \Delta\Lambda$$

Which shifts wavelength:

$$\Delta\lambda_B = 2n_{\text{eff}}\Delta\Lambda$$

This is effectively radiation-induced strain sensing.

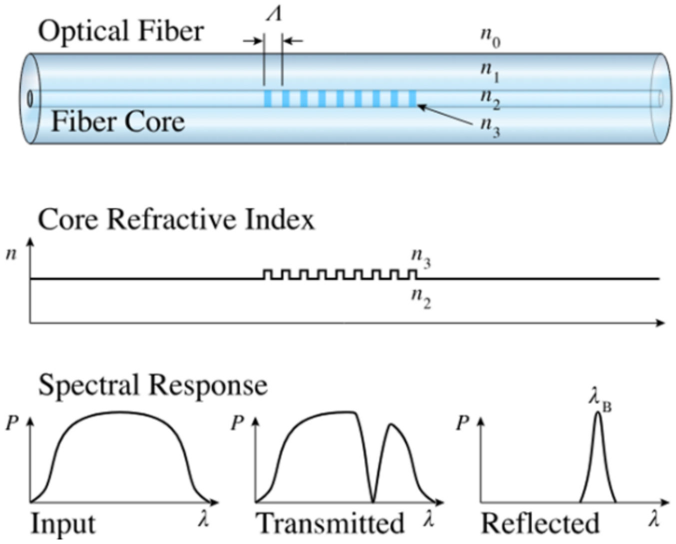

Fig. 1 Fundamental structure and spectral operating principle of a fiber bragg grating (FBG) sensor.

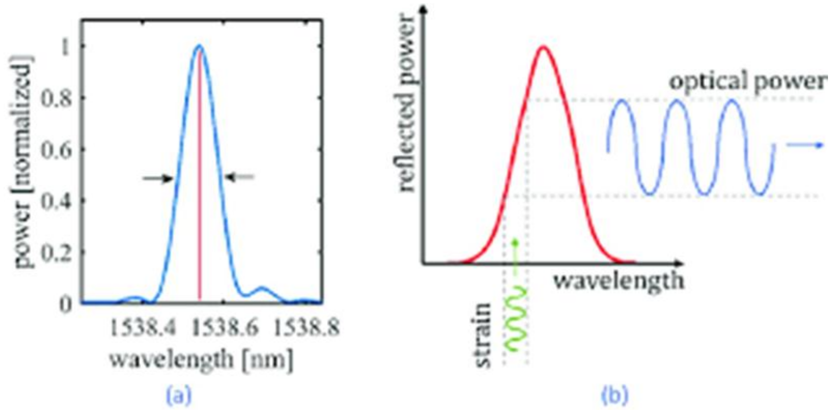

Fig. 2 FBG reflection spectrum shift and optical power response under applied strain.

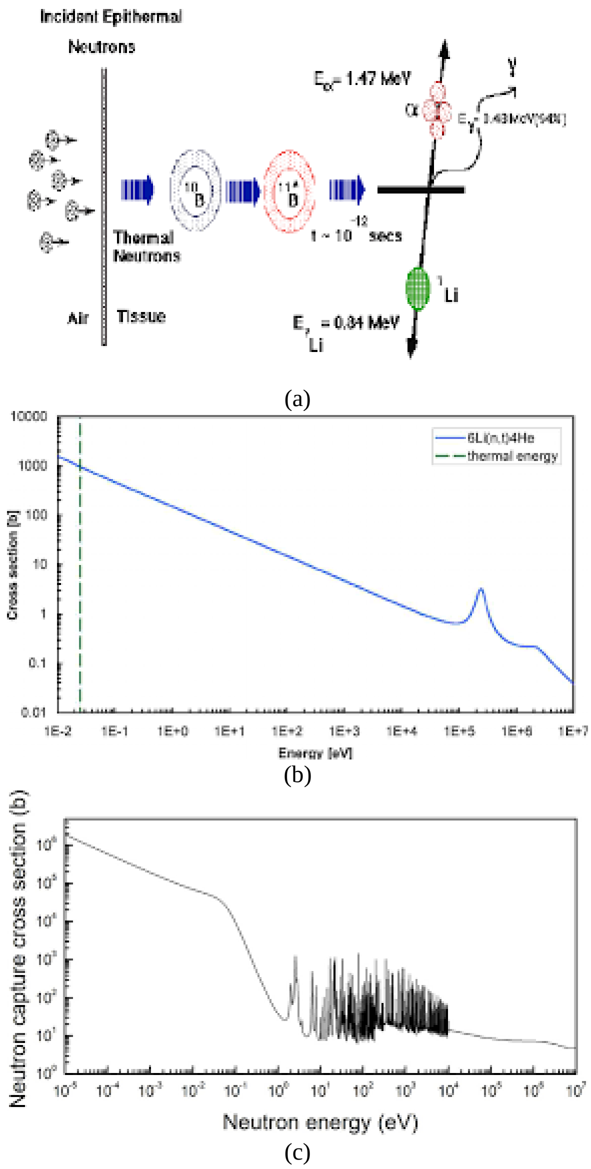

Fig. 3 (a) Fundamental structure and spectral operating principle of a fiber bragg grating (FBG) sensor. (b) FBG reflection spectrum shift and optical power response under applied strain. (c) Neutron capture cross section as a function of neutron energy.

3.3 Mechanism 3: Coating-Based Neutron Conversion: Direct Flux Detection

To improve sensitivity, FBGs can be coated with neutron-reactive materials such as:

- Boron-10 (^{10}B).
- Lithium-6 (^{6}Li).
- Gadolinium (Gd).

Example reaction:

$$^{10}\mathrm{B} + n \rightarrow {}^{7}Li + \alpha + 2.31\,\mathrm{MeV}$$

The reaction produces:

- Alpha particles.
- Heavy ions.
- Localized heating.
- Micro-strain in coating.

That strain transfers to the fiber → wavelength shift.

Now the FBG behaves like a passive neutron flux sensor.

4. How Can FBGs Detect Neutron Flux?

Total wavelength shift:

$$\Delta\lambda_B = \lambda_B \left(\frac{\Delta n}{n} + \frac{\Delta\Lambda}{\Lambda}\right)$$

Including temperature and radiation:

$$\Delta\lambda = S_T \Delta T + S_\epsilon \Delta\epsilon + S_\Phi \Phi$$

Where:

- S_T= thermal sensitivity.
- S_ϵ= strain sensitivity.
- S_Φ= neutron flux sensitivity.
- Φ= neutron flux.

This is where AI/ML becomes powerful:

You can decouple:

- Temperature.
- gamma heating.
- neutron-induced index changes.
- mechanical stress.

Using multi-wavelength FBG arrays.

5. Why FBG Is Attractive for SMRs & Advanced Reactors

Given your interest in ARCO and digital twins:

- FBG advantages:
- Passive (no electrical signal in-core).
- Immune to EMI.
- Radiation hardened (with proper fiber selection).
- Multiplexable (many sensors on one fiber).
- Distributed sensing capability.

Particularly valuable for:

- BWRX-300 in-core monitoring
- LPRM augmentation
- Gamma thermometer enhancement
- Sodium-cooled fast reactors (high EMI environment)
- Microreactors with limited penetrations.

6. Radiation Physics Inside Silica

Neutron damage mechanisms:

1) Elastic scattering → atomic displacement.
2) Inelastic scattering → phonon excitation.
3) Transmutation (minor in SiO_2).
4) Ionization from secondary charged particles.

Displacement damage causes:

- Formation of E' centers.
- Oxygen vacancy defects.
- Non-Bridging Oxygen Hole Centers (NBOHC).

These defects alter the electronic polarizability → change refractive index.

7. Key Engineering Challenge

The main difficulty:

Temperature cross-sensitivity.

In-core environment:

- 300 ℃ to 700 ℃.
- Strong gamma field.
- High neutron flux.

Thus: $\Delta\lambda_{\mathrm{measured}} = \Delta\lambda_T + \Delta\lambda_\gamma + \Delta\lambda_n$

Without advanced signal processing, neutron flux (i.e., Fast vs. Thermal neutron) cannot be isolated cleanly.

This is why your concept of:

AI-DSP-integrated FBG neutron instrumentation is extremely promising.

8. Advanced Concept: Aligned With Your Research

You could design:

- Dual FBG system:
- Bare FBG → temperature reference
- Boron-coated FBG → neutron + temperature
- Subtract signals using ML regression
- Embed into a digital twin model of neutron flux distribution

Even extend to:

- Spectral discrimination using different coatings
- Energy-selective neutron detection
- Real-time in-core 3D flux mapping

For SMRs and autonomous reactors, FBG + AI digital twin is compelling. See Following Table 1.

Table 1 Comparison with traditional neutron detectors.

Detector	*Active/Passive*	*Measures*	*Limitation*
SPND	Active	Local flux	Gamma interference
Fission chamber	Active	Fast response	Electrical noise
LPRM	Active	Local power	Calibration drift
FBG	Passive	Strain/index change	Needs decoupling model

9. In One Sentence: Physics Summary

An FBG detects neutron flux by measuring radiation-induced changes in refractive index and grating spacing caused by neutron interactions with silica or neutron-reactive coatings, resulting in a measurable Bragg wavelength shift.

His matter can be expanded to the following topics that beyond scop of this short communication in more granular content.

- Derive a full neutron-to-wavelength transfer function.
- Develop a reactor-core flux sensing architecture using multiplexed FBG arrays.
- Provide simulation code for wavelength shift vs neutron fluence.
- Draft a patent-style claims section for FBG-based neutron flux monitoring.

10. Summary

This article presents an advanced data assimilation and digital twin framework for real-time neutron flux reconstruction in Boiling Water Reactors (BWRs) using Ensemble Kalman Filtering (EnKF) combined with in-core sensor measurements. The study focuses on a 13-string ×24-axial-node BWR core configuration and investigates the integration of Fiber Bragg Grating (FBG)-based sensing, gamma thermometers (GTs), and flux-related measurements within a nonlinear void-coupled reactor physics model. A three-dimensional lateral and axial neutron flux reconstruction methodology is developed to account for spatial power redistribution and moderation feedback caused by local void fraction variations.

To improve robustness under realistic operating conditions, the proposed estimator augments the EnKF state vector with adaptive bias and gain states for each instrument string. This enables simultaneous estimation of reactor core conditions and online calibration correction for sensor drift, offset, and scaling errors. The framework incorporates local channel-flow distributions, thermal-hydraulic feedback effects, and nonlinear observation models linking neutron flux, temperature, and void fraction behavior.

Simulation results demonstrate that the adaptive EnKF architecture can accurately track transient reactor behavior, reduce flux reconstruction error, and maintain estimator stability in the presence of sensor uncertainties. Additional diagnostic visualizations, including flux measurements, GT temperature responses, bias and gain convergence, and RMSE evolution, illustrate the performance of the proposed approach. The methodology provides a foundation for future AI-enhanced digital twin systems and next-generation in-core monitoring architectures for advanced BWR and Small Modular Reactor (SMR) applications using distributed fiber-optic sensing technologies.

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