Recent Advances in Reactor Noise Analysis Applications

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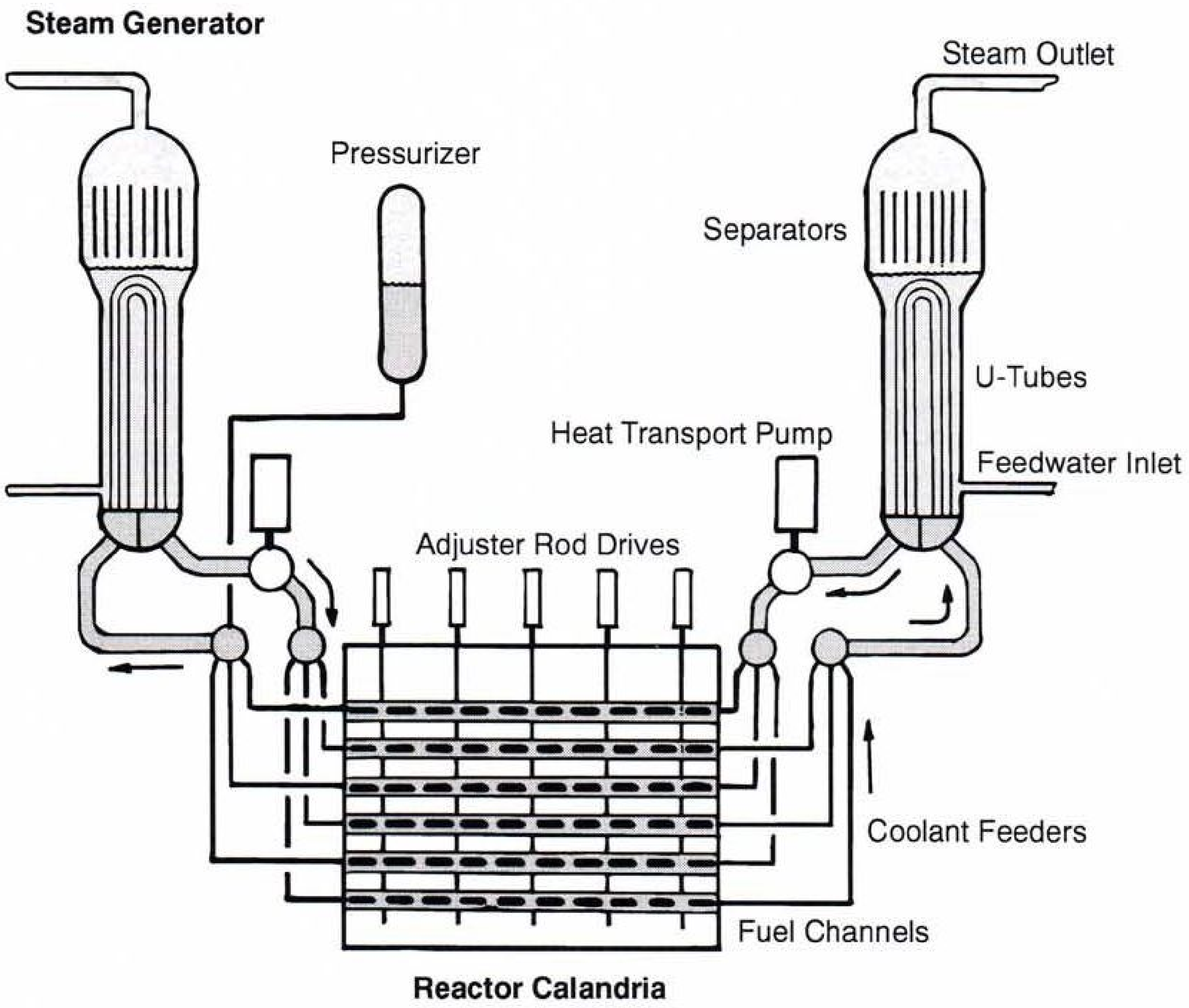


33rd International Meeting on Reactor Noise, IMORN-33
Grenoble, France 2026 July 6-8

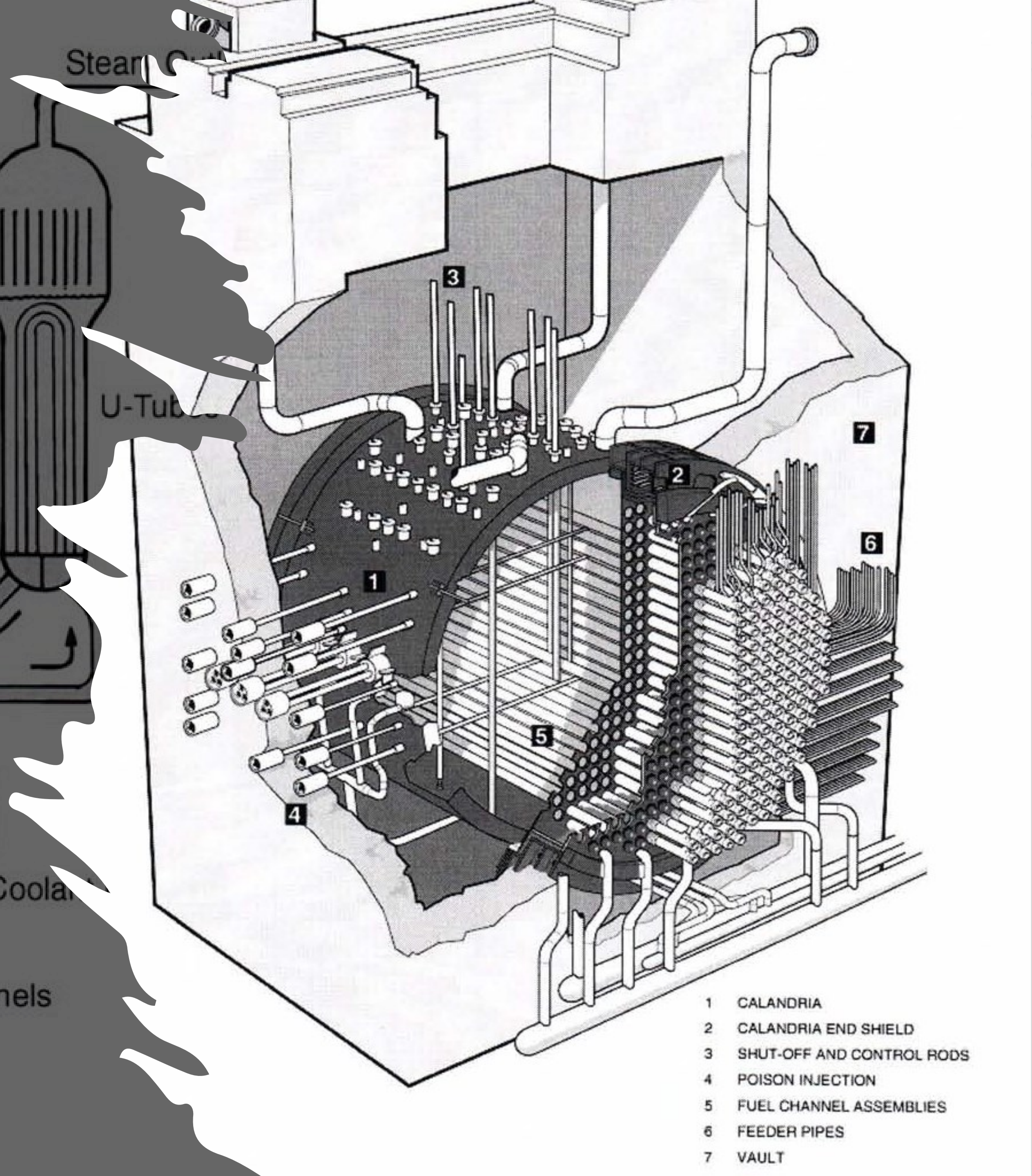
153-120000-001-000

The CANDU Pressurized Heavy Water Reactor system - a Pressure Tube reactor

- 360 – 480 Fuel Channels per reactor
- 12 Fuel Bundles per Fuel Channel
- 100-200 Horizontal and Vertical In-Core Flux detectors per reactor
- Up to 9 Ion Chambers just outside the reactor core
- 14 Liquid Zone Control units for reactor control

Also:

- Coolant Flow (differential pressure) sensing on 20 – 40 Fuel Channels
- Redundant Pressure and Flow (differential pressure) sensors on 8 inlet and outlet headers
- Pressure (P) and differential pressure (DP) sensed via long (25-50 m) instrument lines connecting to P and DP transmitters



Outline

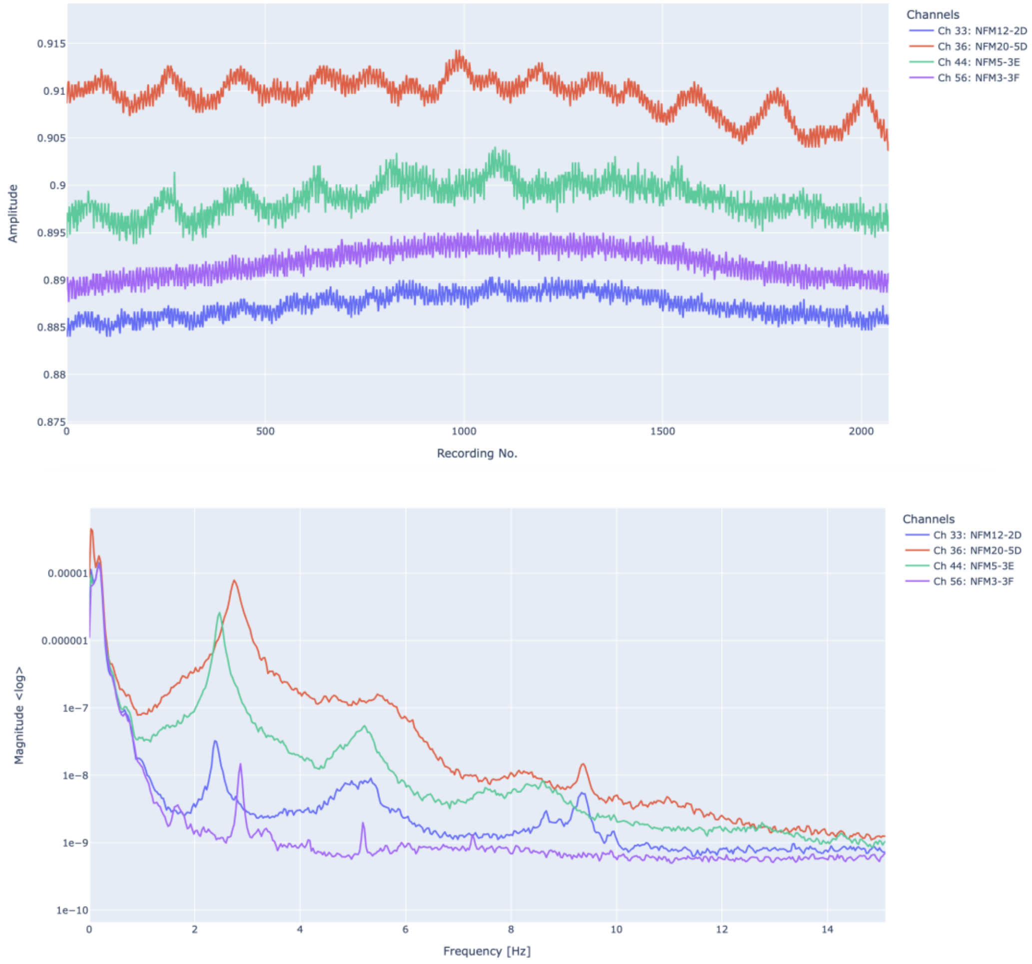
Noise Analysis: Statistical and spectral analysis of small signal fluctuations around steady state (DC) value

Applicable to pressure, differential pressure (flow, level), temperature, position, reactivity, neutron flux

Advanced applications leverage simulation, modeling, data driven diagnostics and automated data analysis

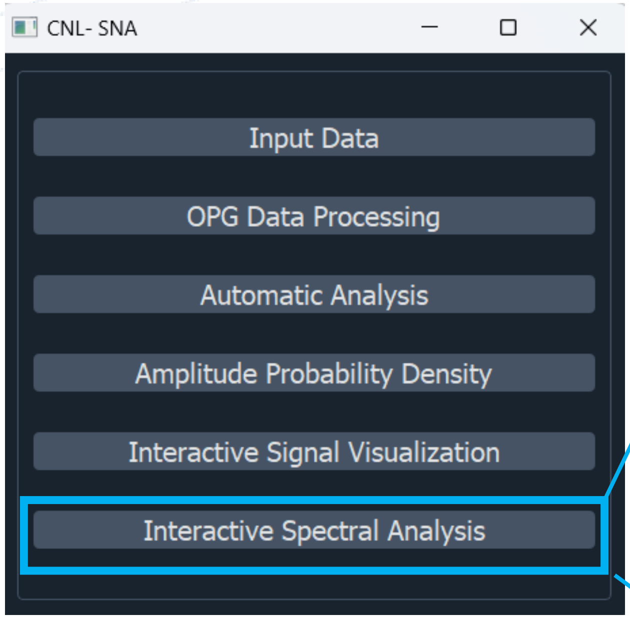
Topics:

1. CNL Signal Noise Analysis (CNL-SNA) software package
2. Signal validation and fault detection of CANDU core instrumentation
3. Prompt fraction of In-core flux detectors (ICFDs)
4. Leak detection in primary heat transport instrument lines
5. Vibration-based condition monitoring of CANDU fuel channels
6. Experimental validation of neutronics response to component vibration in ZED-2 - a heavy water zero power reactor

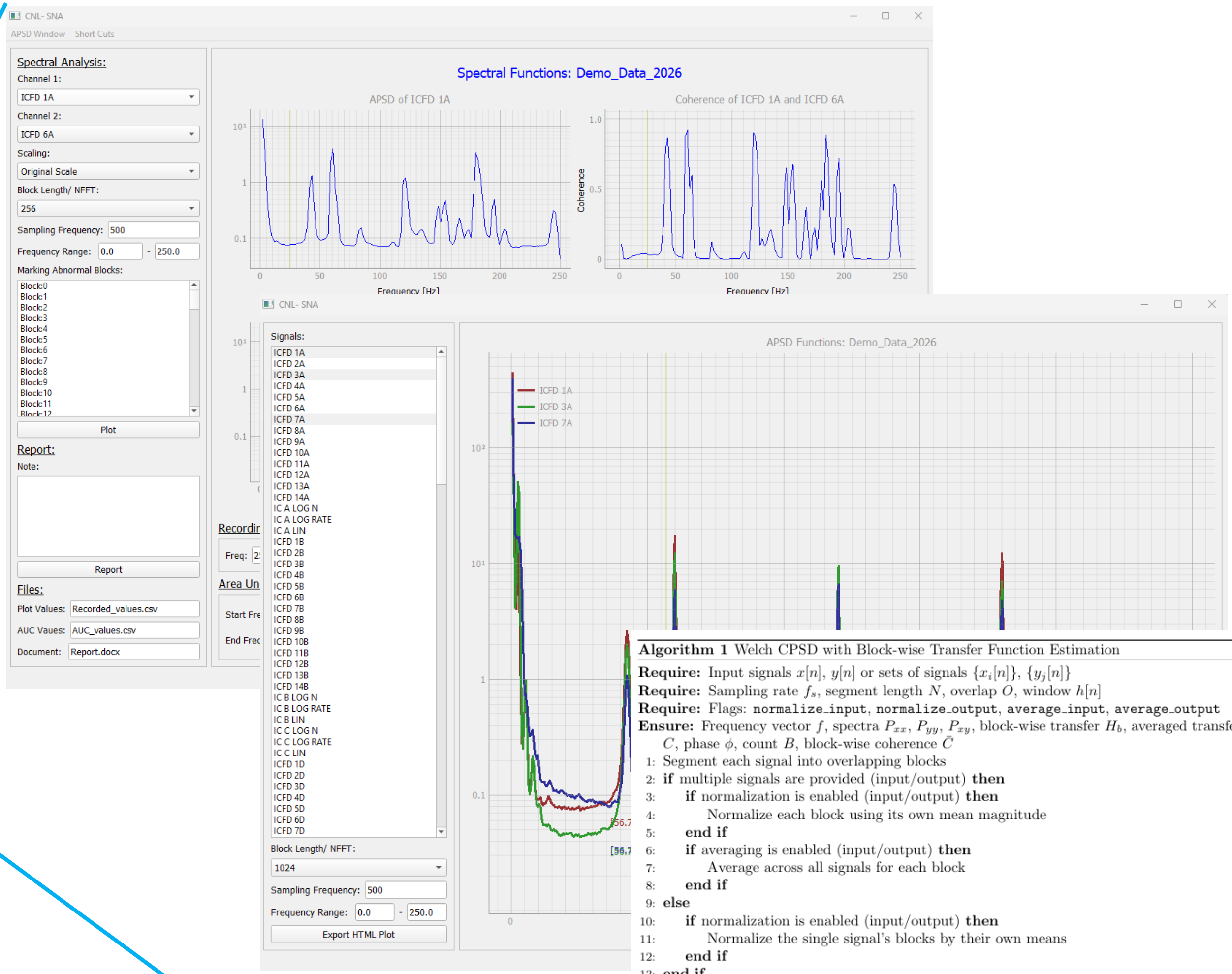


Time series data and Auto-Power Spectral Density (APSD) of ICFDs in a CANDU reactor

1. Modules and Functionalities of the CNL-SNA Software Package



Spectral Analysis: Allows the user to estimate **APSD** (Auto Power Spectral Density), **CPSD** (Cross Power Spectral Density), **Coherence, Transfer Function,** and **Phase** between two signal pairs.



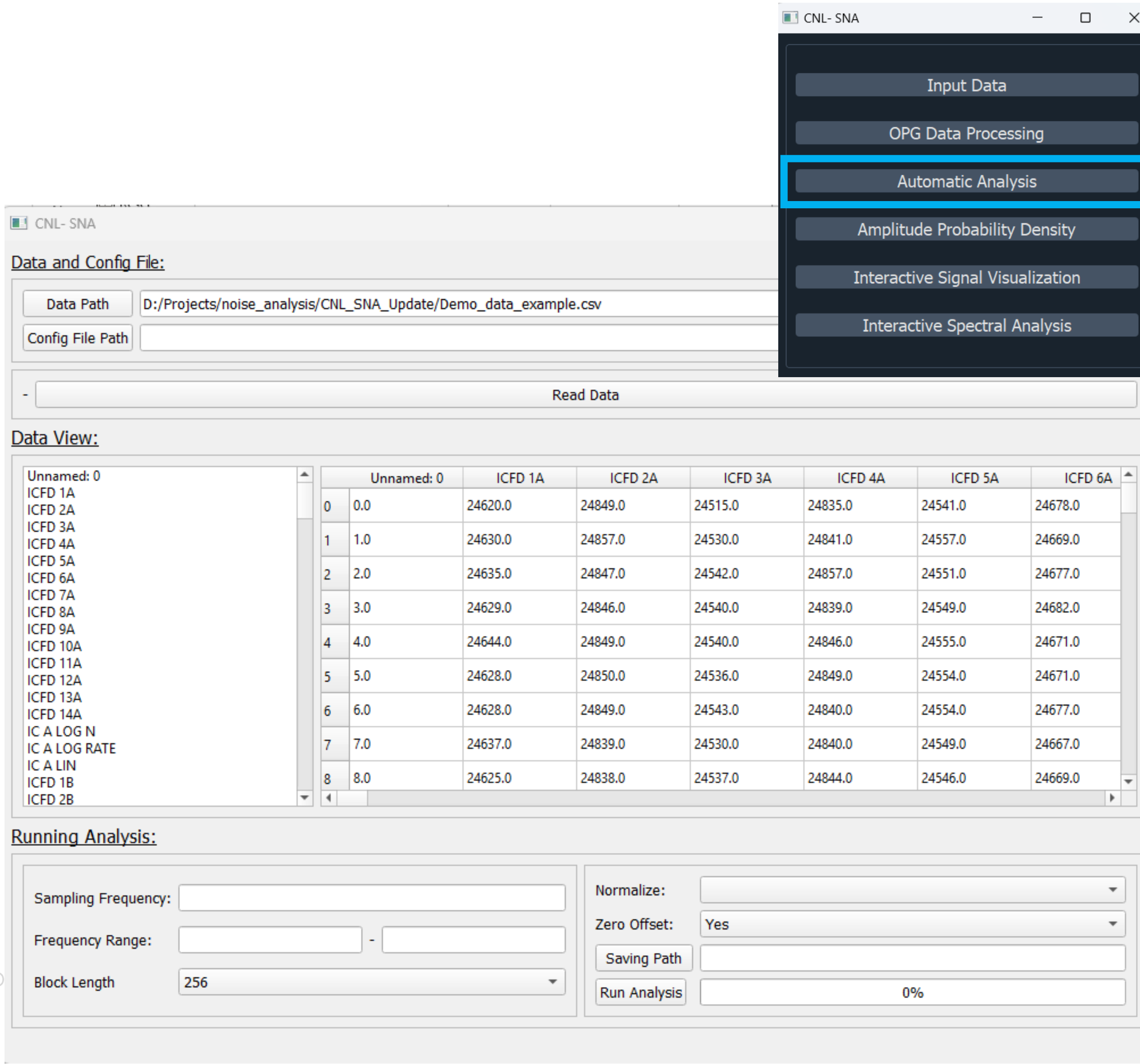
Algorithm 1 Welch CPSD with Block-wise Transfer Function Estimation

Require: Input signals $x[n]$, $y[n]$ or sets of signals $\{x_i[n]\}$, $\{y_j[n]\}$
Require: Sampling rate f_s, segment length N, overlap O, window $h[n]$
Require: Flags: `normalize_input`, `normalize_output`, `average_input`, `average_output`
Ensure: Frequency vector f, spectra P_{xx}, P_{yy}, P_{xy}, block-wise transfer H_b, averaged transfer H, coherence C, phase ϕ, count B, block-wise coherence $\bar{C}$

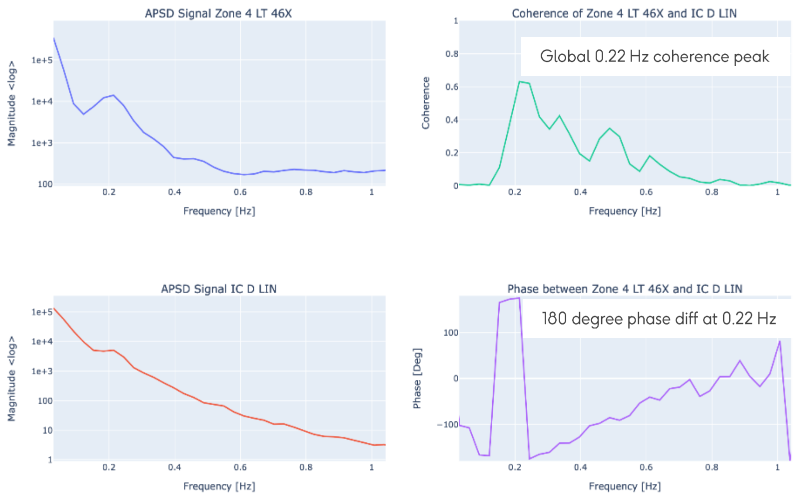
```
Segment each signal into overlapping blocks
if multiple signals are provided (input/output) then
    if normalization is enabled (input/output) then
        Normalize each block using its own mean magnitude
    end if
    if averaging is enabled (input/output) then
        Average across all signals for each block
    end if
else
    if normalization is enabled (input/output) then
        Normalize the single signal's blocks by their own means
    end if
end if
Optionally detrend each block
Apply window h[n]
Compute FFT X[k], Y[k]
Compute scaled APSD and CPSD
If N is even: Multiply bins 1 to N/2 − 1 by 2. Else: Multiply bins 1 to end by 2
Compute block-wise transfer function: H_b[k] = P_xy^(b) / P_xx^(b)
Compute block-wise coherence: C^(b)[k] = |P_xy^(b)[k]|^2 / (P_xx^(b)[k] · P_yy^(b)[k])
Average all block-wise values: P_xx, P_yy, P_xy, H, C̄
Compute traditional coherence: C[k] = |∑ P_xy|^2 / (∑ P_xx · ∑ P_yy)
Compute phase: φ[k] = ∠P_xy[k]
```

1. Modules and Functionalities of the CNL-SNA Software Package

- Designed to execute automated processing of noise signals, delivering comprehensive, systematic results
- Encompasses all typical signal sets that can be selected and processed in noise measurements across all CANDU designs
- Generates Noise Spectral Functions for signal validation of Ion Chambers (IC), In-Core Flux Detectors (ICFDs), Liquid Zone Controller (LZC) Level Signals, LZC Level and Reactor Regulating System (RRS) ICFD signals, Noise coupling between the LZC Level signals and the IC-LIN signals

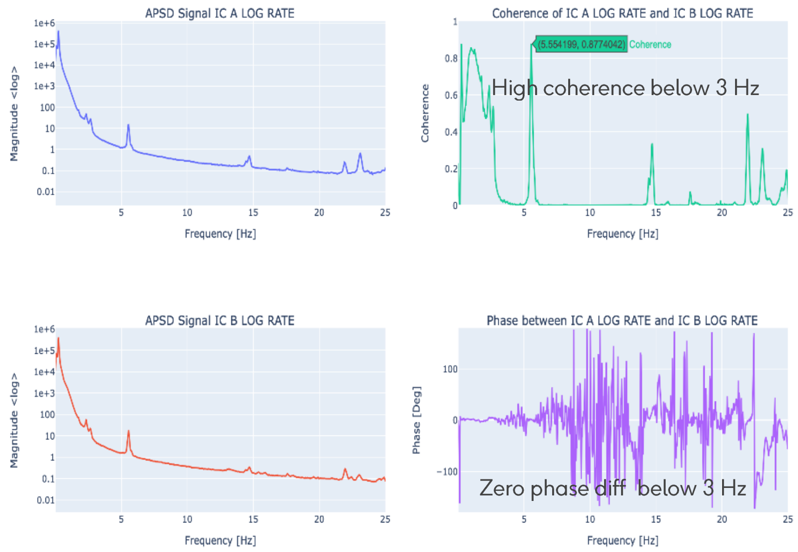


2. Neutronics signal validation & incipient fault detection

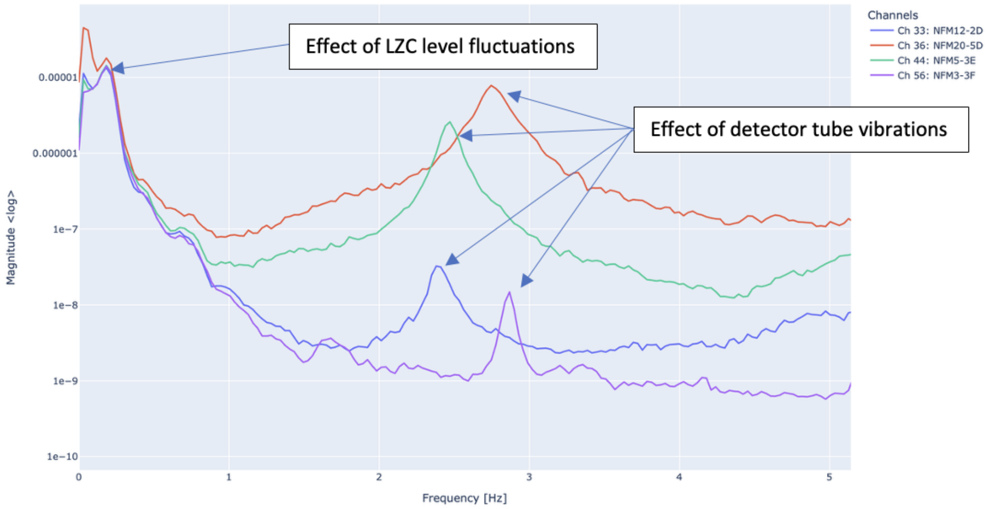


Coupling between Linear Ion Chamber (IC-LIN D) and Liquid Zone Control (LZC Z4) level

- ICFD, IC and LZC signal fluctuations recorded at steady-state full-power operation are coupled/correlated as a function of frequency



Coupling between Ion Chamber Log Rate Signals (IC-LOG RATE A and IC-LOG RATE B)

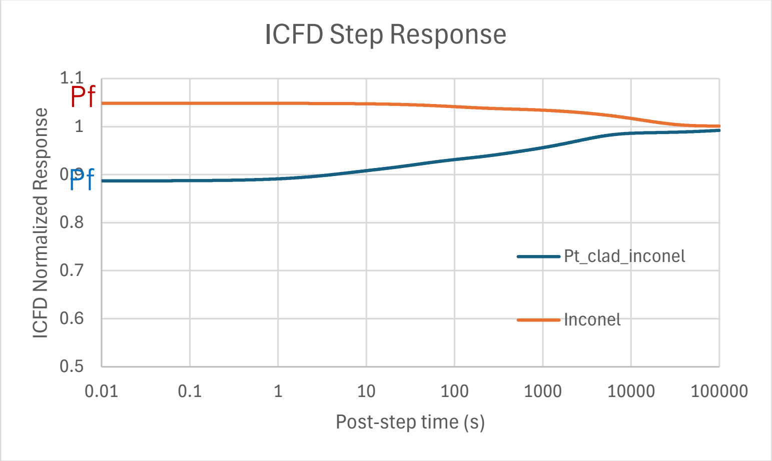


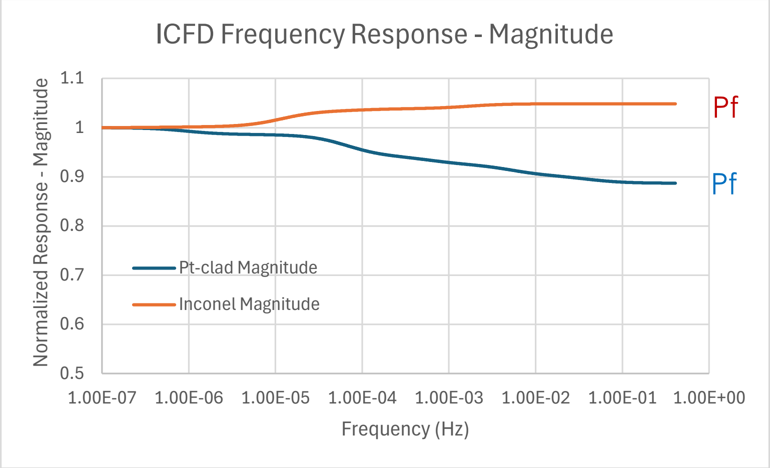
Spectral functions (APSD) of noise signals of vertical ICFDs

2. Neutronics signal validation & incipient fault detection

- Station measurements show that ICFD, IC and LZC signal fluctuations recorded at steady-state full-power operation are correlated as a function of frequency, displaying well-defined coherence and phase functions (noise signatures).
- We derived a large number (100 to 200) of these noise signatures from time series measurements in CANDU stations and learned how they look like when the dynamics of ICFD, IC and LZC signals are normal.
- This represents a measurement-based baseline of normal dynamics of ICFDs, ICs and LZCs, directly derived from measurements (as opposed to modelling).
- To validate signal dynamics at steady-state operations, (1) need to measure the corresponding time series, (2) generate the spectral noise signatures and (3) compare them with the normal baseline of noise signatures.
- Deviations can be interpreted as consequences of either known changes in the system or as signal faults, therefore the noise-based technique can be used as a tool for signal validation and fault detection.
- Details of signal validation and fault diagnosis methodology in O. Glockler presentation (this session)

3. In-Core Flux Detector (ICFD) prompt fractions

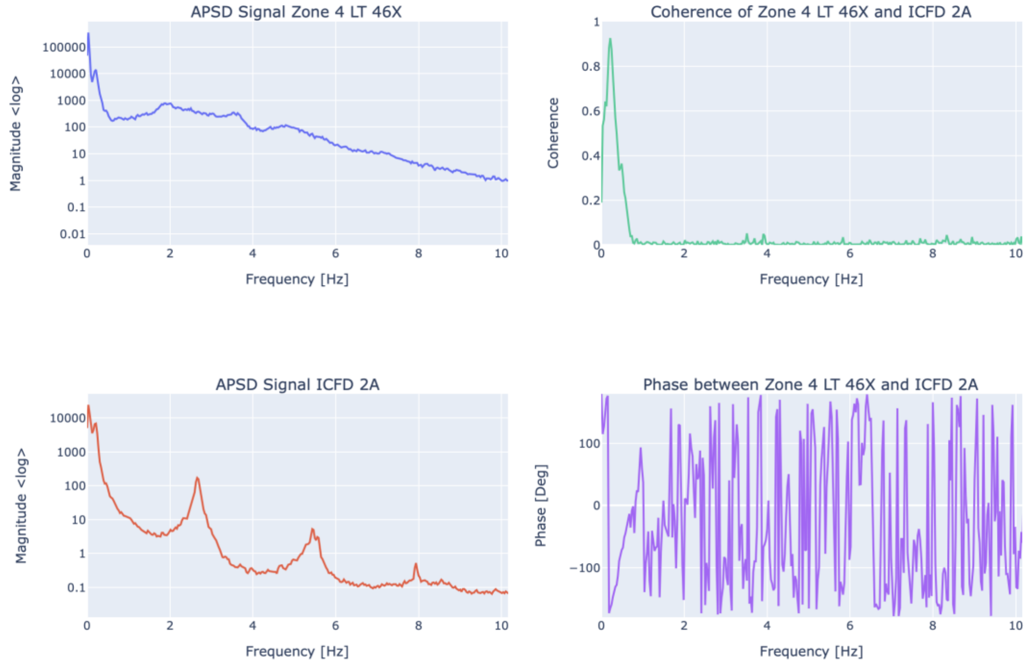




- **Prompt Fraction (Pf)** - fractional prompt response to step change in neutron flux – measure of "speed" of safety system ICFD response; differs with ICFD type;
- **Step Response** ~ Approximated by Trip Response (Time domain, Ion Chamber (IC) reference run-down flux)
- **Frequency Response** ~ Noise Analysis Transfer Function w.r.t. local reference flux
- In CANDU reactor systems, ex-core IC signal represents globally coherent reference flux at ~0.2 Hz
- LZC level variations produce additional local flux perturbations
- The ICFD transfer function magnitude w.r.t. IC signal at ~ 0.2 Hz, corrected for local flux perturbations is the ICFD prompt fraction

3. In-Core Flux Detector (ICFD) prompt fractions

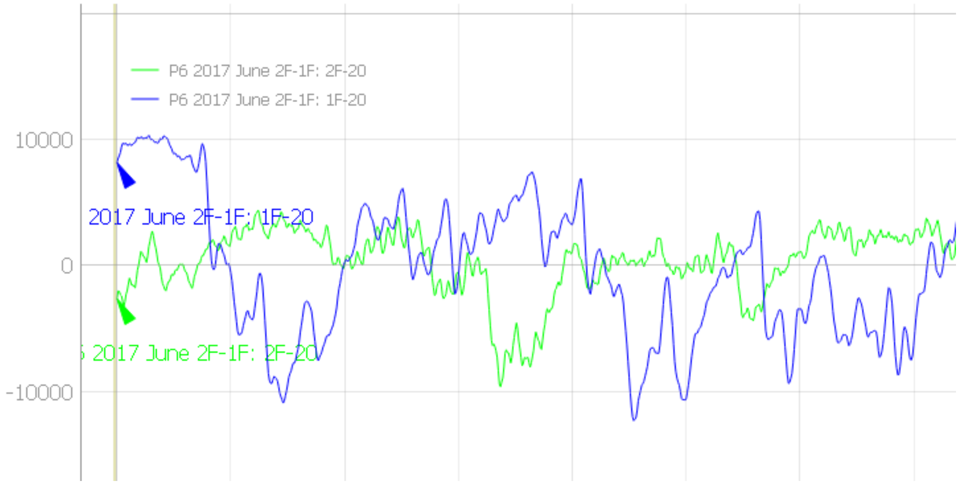
- **ICFD prompt fractions estimated at full power steady state from response at 0.2-0.25 Hz global flux oscillation.**
- **Benefit - Early indication of safety signal degradation:**
  - Outage planning cushion for investigation and remediation
  - Avoid reduced trip margin and unplanned outages
- **Progress and next steps**
  - Uncertainty reduction and quantification methodologies formulated and applied to existing datasets
  - ICFD response to local variable absorber (LZC) vs global flux variation (Ion Chambers) formulated
  - Effect of lead cable response (Pt-clad vs Inconel ICFDs) under investigation
  - Methodology validation on station data under progress



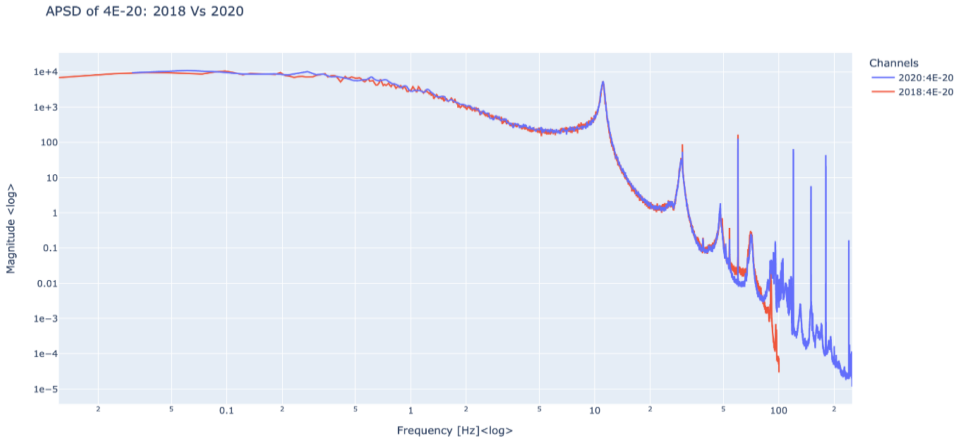
APSD, coherence and phase functions showing coupling between Zone 4 Liquid Zone Control level fluctuations and ICFD 2A in a CANDU station

4. Primary Heat Transport (PHT) Instrument Pressure Line Leak Detection

- Recurrent leaks in PHT instrument lines – forced outages, difficulties in detection, mitigation planning (e.g., inside feeder cabinets)
- Noise Analysis is routinely used for Transmitter Response Time Verification in some stations – leak detection requires same type of data
- Shape of high frequency noise spectrum of transmitter signals is sensitive to instrument line condition
- Station flow noise data across multiple years analyzed – stable instrument line condition indications
- Automated resonance peak fitting algorithm developed
- Finite Element Modeling (Computational Fluid Dynamics + Acoustic Harmonics) of leak signature developed



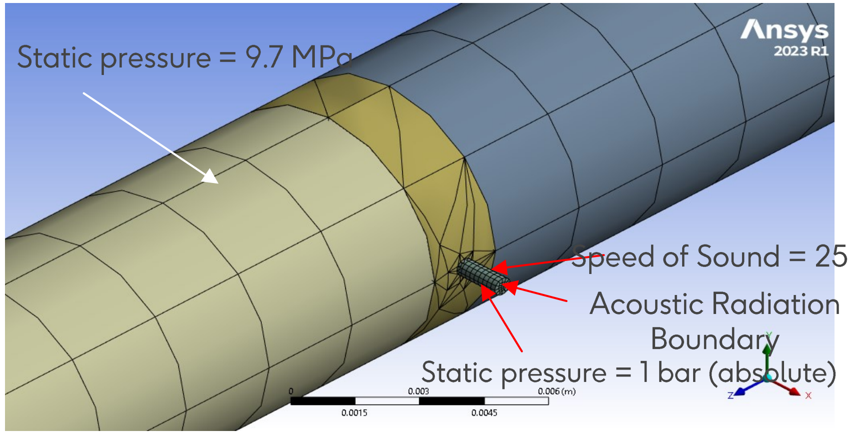
Time domain: trends are not evident,



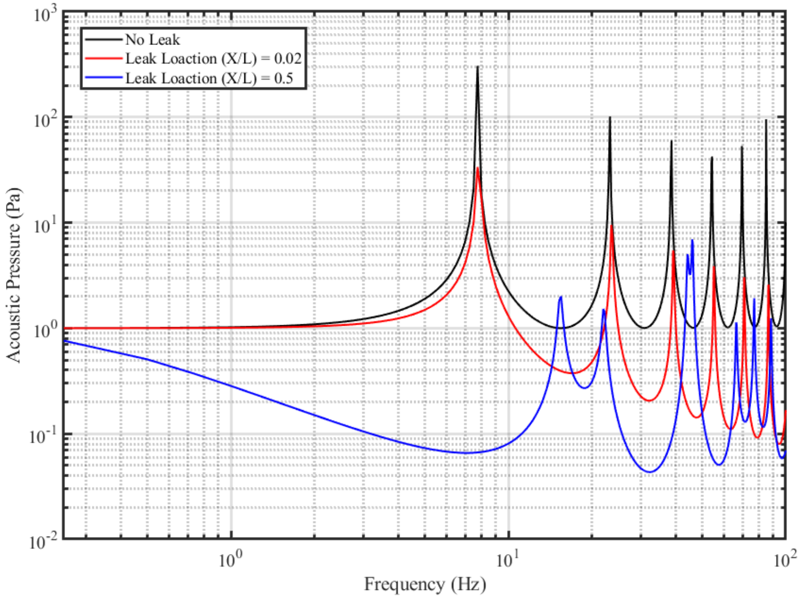
APSD of Flow Transmitter FT-3E: 2018 vs. 2020

4. PHT Instrument Pressure Line Leak Detection (continued)

- **Leak Signatures:**
  - Decreasing response with frequency
  - Shift in resonance frequencies – caused by mismatch in speed of sound inside the instrument line below and above leak: 1323 m/s at 20 ^{o}C; 787 m/s at 270 ^{o}C
  - Frequency shift related to location of leak
- **Station Implementation**
  - Noise data acquisition equipment exists in all stations
  - Connection procedures exist for transmitter response time verification
  - Baseline noise signatures can be established as soon as stations are ready
  - Data Acquisition Equipment Upgrades will facilitate on-line monitoring
- **Benefits** (compared to current visual inspection):
  - Outage time reduction 4.5 days
  - Outage dose reduction 8.6 Rem



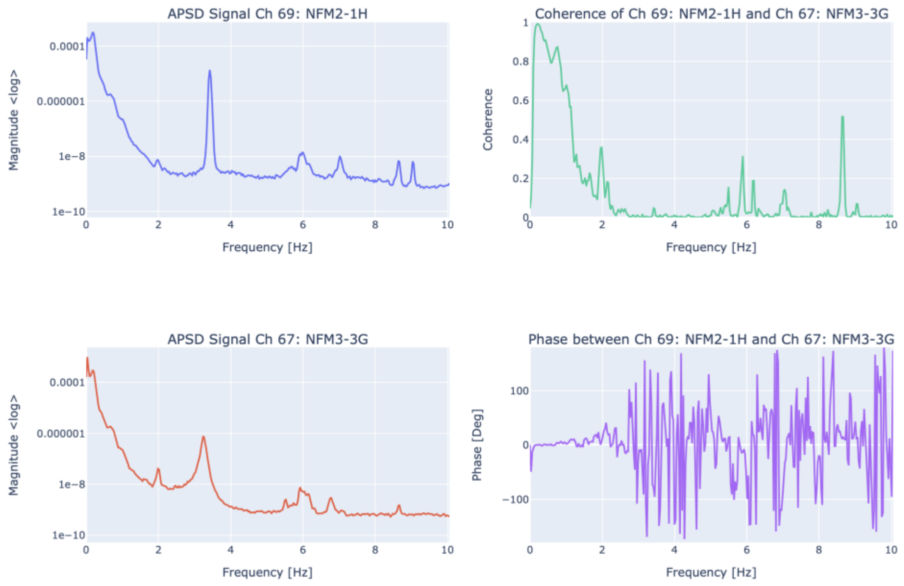
Computational Domain of Leak



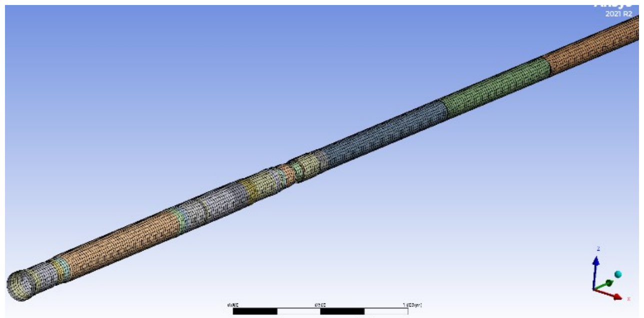
IL Frequency Response with and without leak

5. Condition monitoring of fuel channels

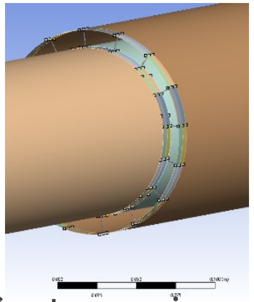
- Fuel Channel vibrations produce correlated peaks in neutron noise spectra of nearby ICFDs and ICs
- Changes in fuel channel vibration frequencies linked by modeling to aging and degradation mechanisms – creep, elongation, sag, embrittlement, spacer movement, PT-CT contact, end-fitting degradation
- **Benefit** – On-line monitoring of fuel channel condition:
  - Early warning of fuel channel degradation
  - Outage planning cushion for investigation and remediation
- **Station Implementation**
  - Data Acquisition equipment, protocols exist at all stations
  - Data driven monitoring program under development



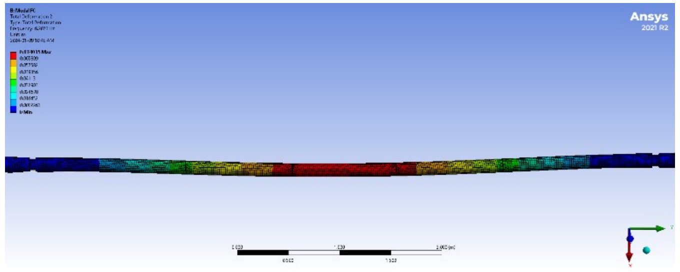
Examples of fuel channel vibrations as sensed by SDS2 horizontal ICFDs located in different flux detector assemblies.



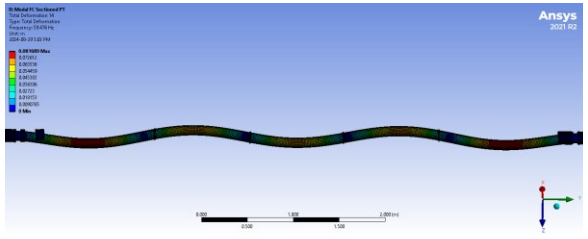
Half span of fuel channel ass'y



Garter spring model



First mode – 5.5 Hz



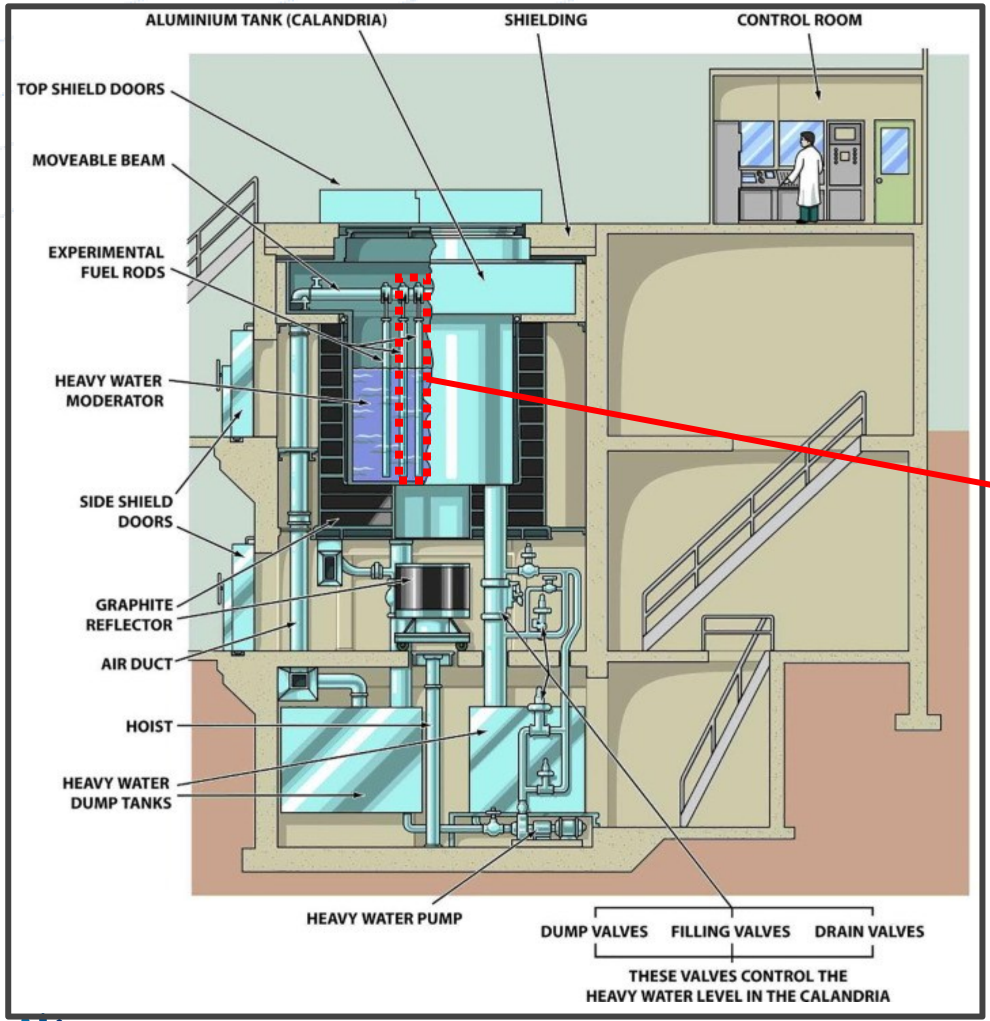
Seventh mode ~ 59.4 Hz

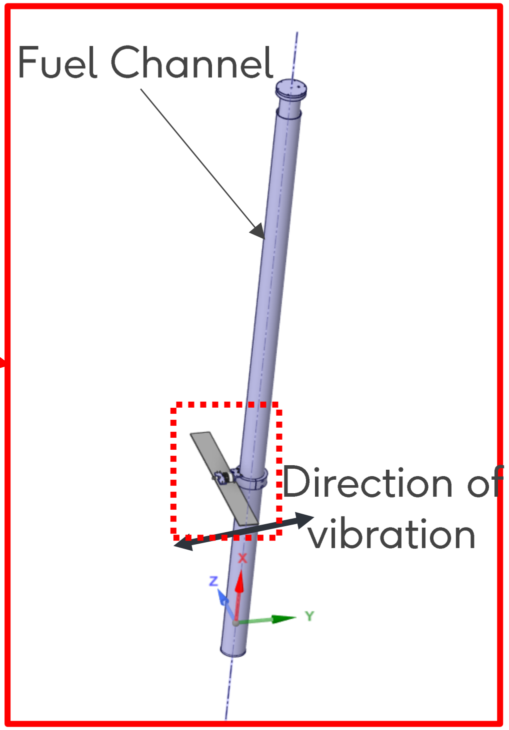
6. Experimental Validation of Neutronic Response to Vibration

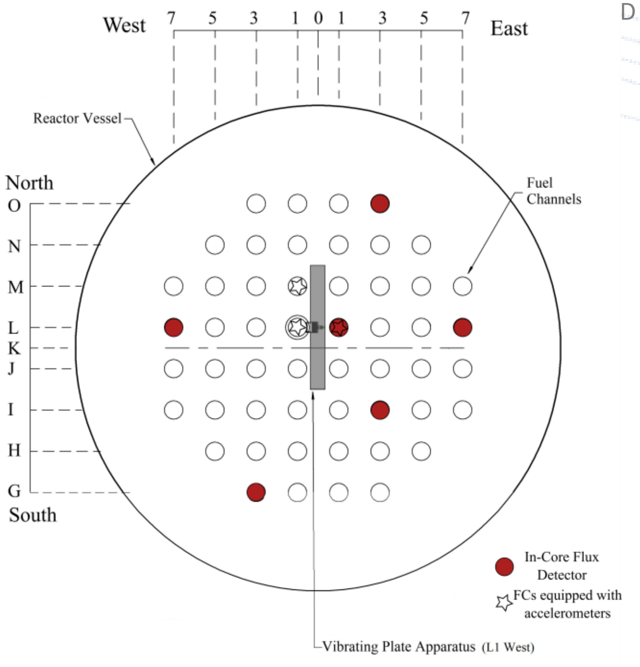
Objectives:

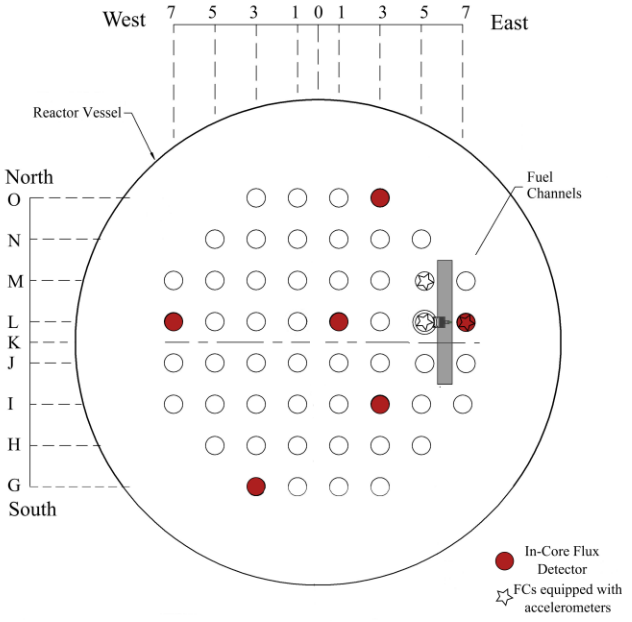
- Develop an experimental setup capable of inducing controlled vibrations within ZED-2 (a zero-power, heavy-water-moderated, tank-type reactor).
- Establish transfer functions for the neutron response of an easily characterizable vibrating structure.
- Assess the effect of different neutron absorption cross sections (absorber vs transparent).
- Assess the effect of flux profile and spatial effects.

6. Experimental Design in the ZED-2 Reactor

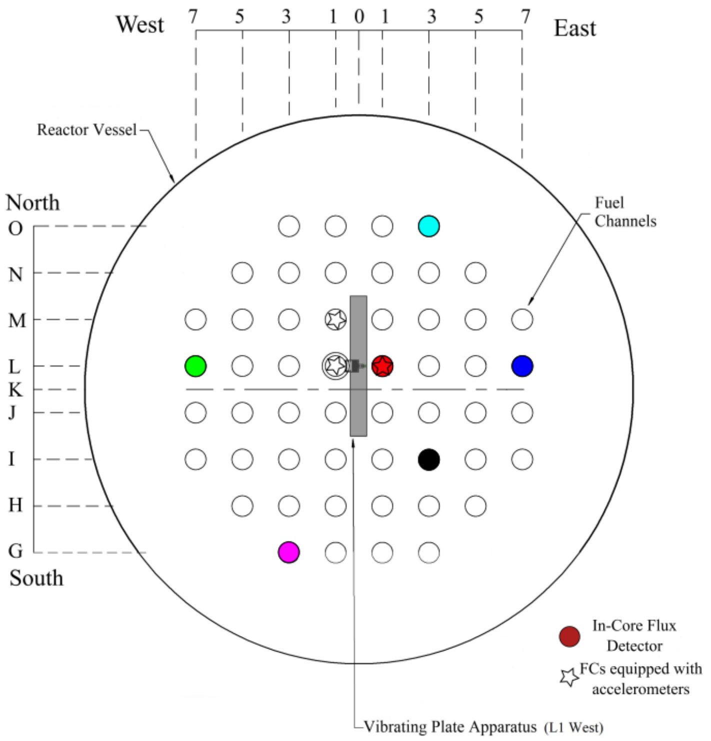


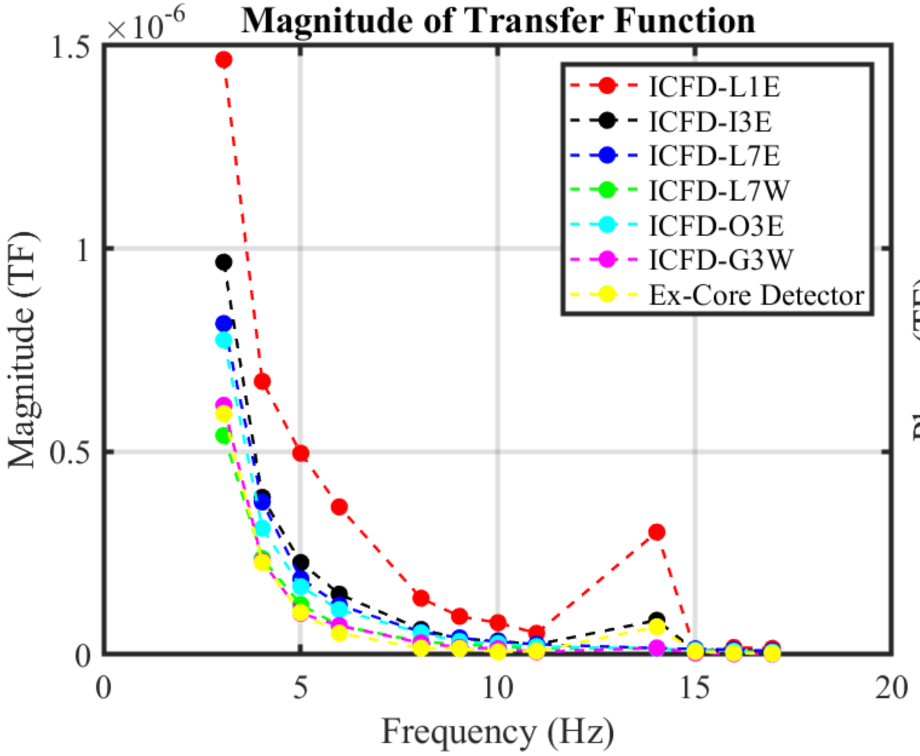


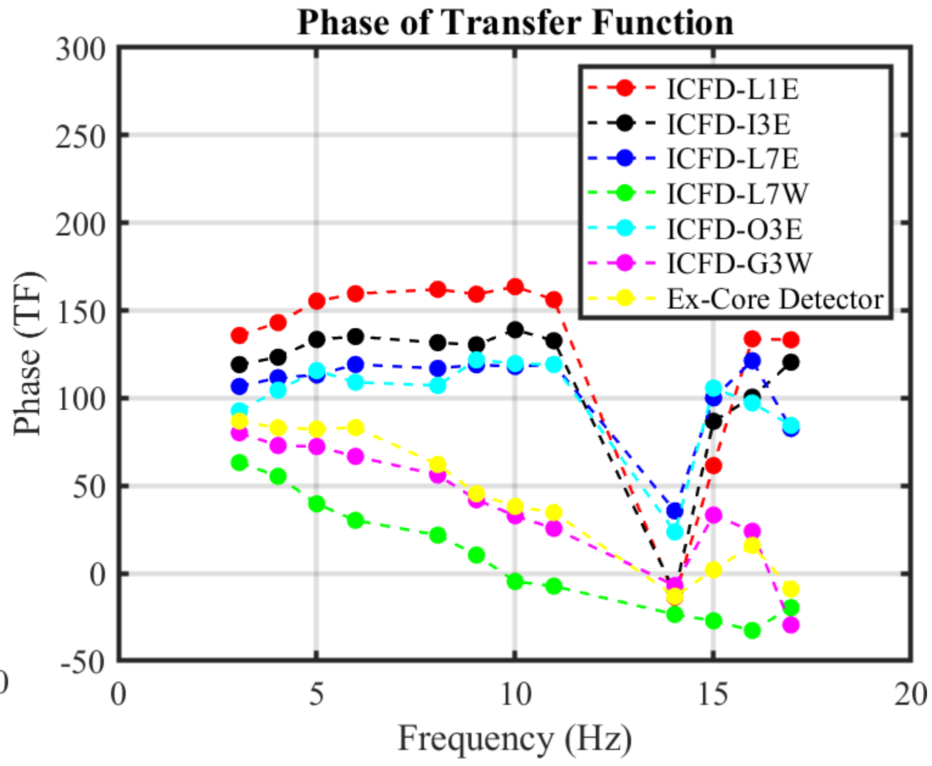




6. Experimental Results (Lattice 1) – Transfer Function

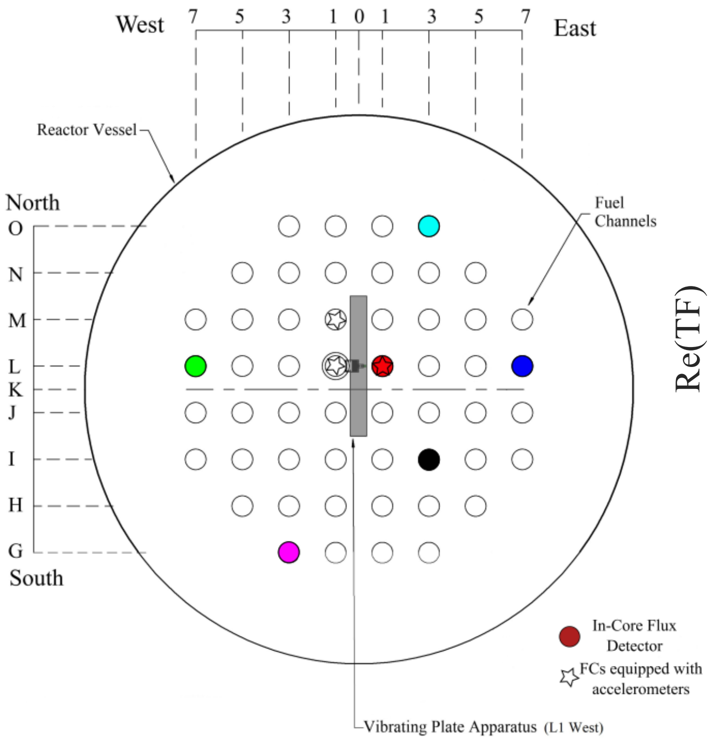


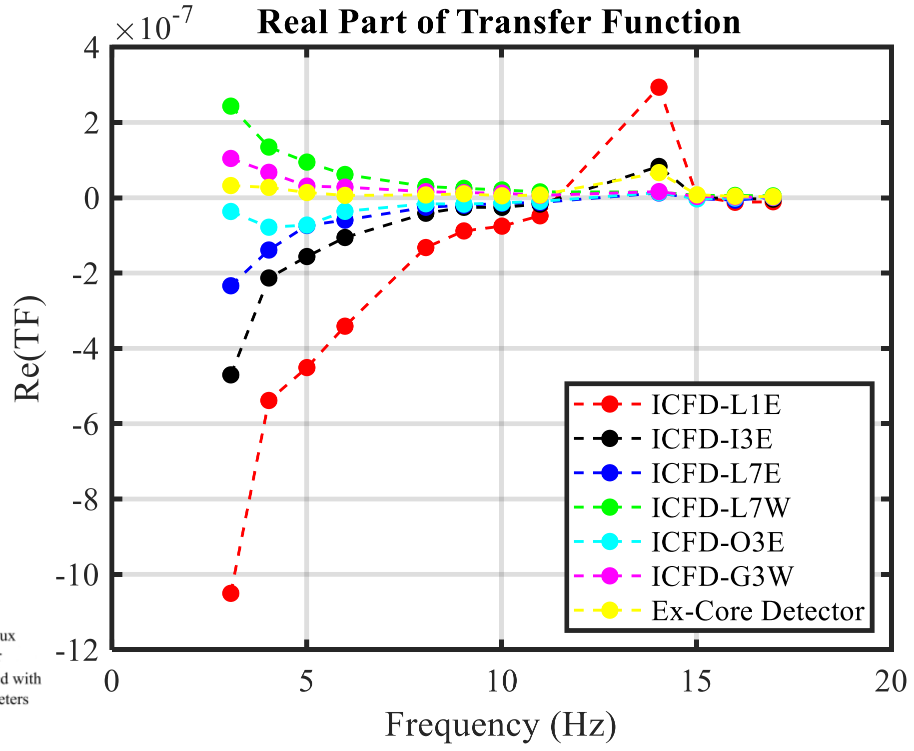


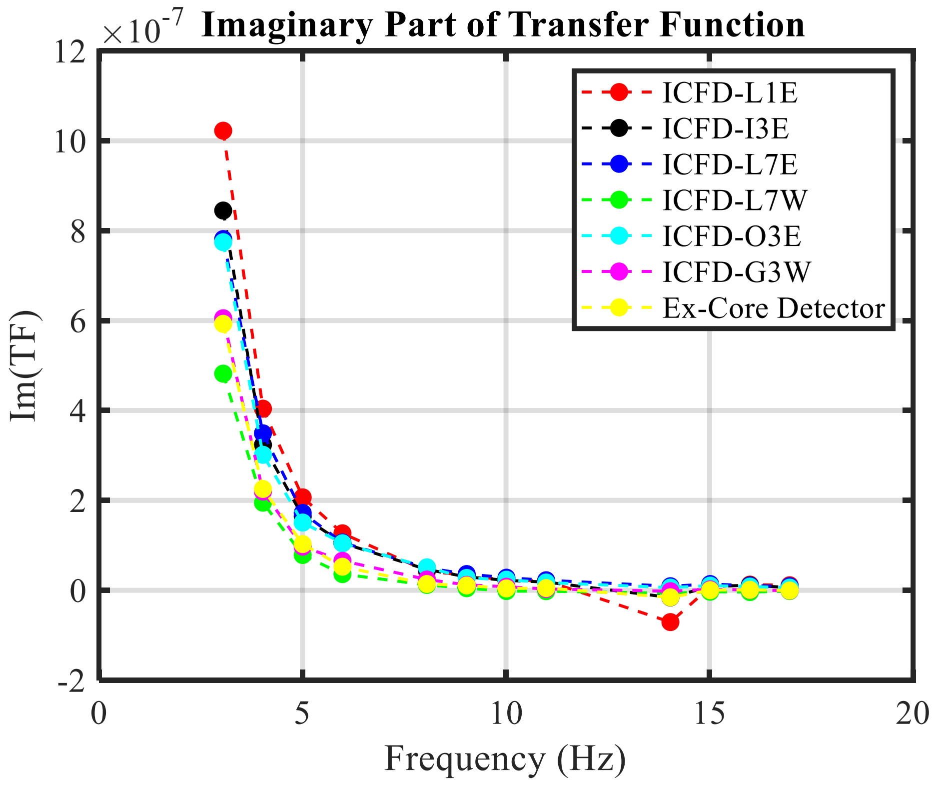


$$\textbf{Transfer Function (TF)} = \frac{\textit{Normalized Neutron Flux}}{\textit{Plate Acceleration}}$$

6. Experimental Results (Lattice 1) – Transfer Function … (Cont.)



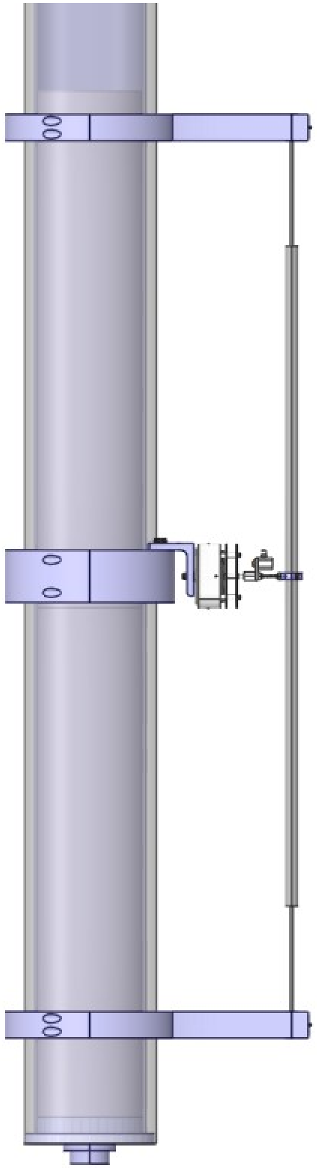




$$\text{Transfer Function (TF)} = \frac{\textit{Normalized Neutron Flux}}{\textit{Plate Acceleration}}$$

6. Experimental Validation of Neutronic Response to Vibration: Conclusion and Future Work

- Conclusion:
  - Vibration-induced neutron noise experiments at ZED-2 were performed for a range of excitation frequencies (3.0 Hz – 17.0 Hz) to examine the detected neutronic signal behavior resulting from mechanical vibrations.
  - The resulting neutron flux amplitude and phase induced by vibrations exhibit frequency-dependent behaviour.
  - The amplitude of neutron signals caused by vibrations decrease with frequency and with distance from the vibration source.
  - The phase varies with distance pointing to the possibility of using phase for localizing the vibration source.
- Future Work:
  - Conduct test campaign with flexible oscillator with known mode shape.
  - Use findings to support validation of neutron noise simulation tools.



Acknowledgements

Canadian Nuclear Laboratories' Laboratory Directed Science & Technology (LDST) Program

Atomic Energy of Canada Limited's Federal Nuclear Science & Technology (FNST) Work Plan

Further Reading:

1. El Bouzidi, S., Sur, B., Feenstra, P., St. Pierre, B., Alziadeh, M., Gadelhak, I., Burlock, M., Atfield, J. and Yaraskavitch, L. (July 2025). In-Reactor Experiments to Enhance Neutron Noise Analysis Techniques for Vibration Monitoring. In Pressure Vessels and Piping Conference (Vol. 89077, p. V004T04A015). American Society of Mechanical Engineers.

2. El Bouzidi, S., Sur, B., Feenstra, P., Pierre, B.S., Alziadeh, M., Gad-el-Hak, I., Burlock, M., Atfield, J. and Yaraskavitch, L. (August 2025) .Experimental Investigation of Vibration-Induced Neutron Noise. Part II: Experimental Results. In 28th International Conference on Structural Mechanics in Reactor Technology.

Thank You

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