Development of Hydrogen Transport Models for High Temperature Metal Hydride Moderators

March 3-5, 2026

Prof. Jeffrey C. King, Colorado School of Mines

Project Motivation

- Minimizing reactor core size is an important consideration in many (all?) microreactor concepts
- The incorporation of a moderator into a reactor core can reduce the amount of fissile material required for criticality
  - This can lead to reduced size or reduced enrichment
- The high temperatures expected in most microreactor designs limit the use of water (the most common moderating material)
- Metal (Zr and Y) hydrides can be nearly as effective as water at elevated temperatures
- Understanding the fabrication, incorporation, and performance of high temperature metal hydride moderators is an enabling technology for the development of future microreactors
- There is a need to develop validated computational methods to predict the short- and long-term reactor performance impacts from hydrogen transport in zirconium- and yttrium-hydrides
- Better computation methods will depend on better migration data

MRP Microreactor Program

Driving Forces for Hydrogen Migration

- Hydrogen in zirconium is driven by three gradients in the material[1]
  - Concentration,
  - Temperature, and
  - Stress
- The generalized equation for hydrogen migration flux is:[1]

$$J_H = -D_H * \left(\underbrace{\nabla \cdot C_{ss}}_{\text{Fickian}} + \underbrace{\frac{Q^* C_{ss}}{RT^2} * \nabla \cdot T}_{\text{Soret Effect}} + \underbrace{\frac{V^* C_{ss}}{RT} * \nabla \cdot \sigma_h}_{\text{Stress Cross-Effect}} \right)$$

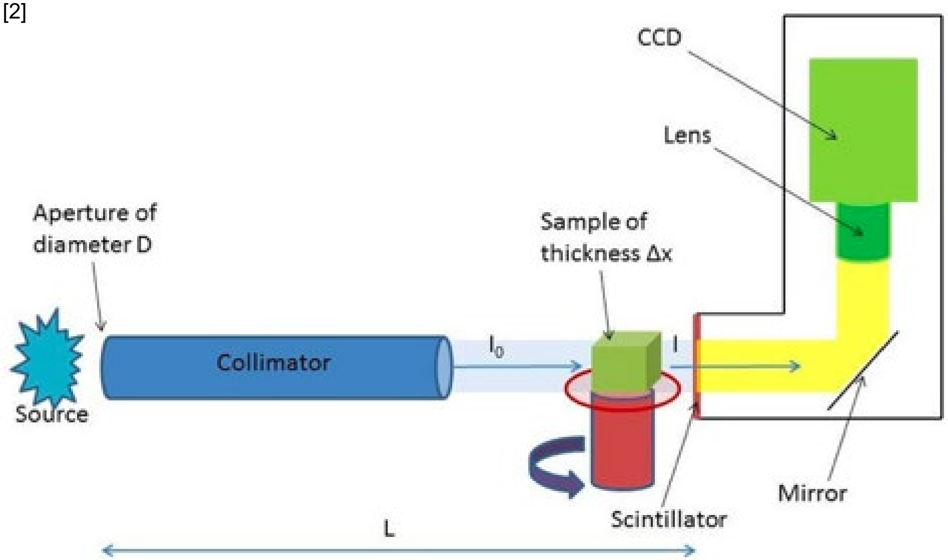
- Interstitial solutes will diffuse towards areas of:[1]
  - Low solid solution concentration
  - Low temperature
  - High tensile hydrostatic stress
- Accurate measurements of D_H, Q^*, V^* are required for accurate modeling.

[1] B. F. Kammenzind, B. M. Berquist, R. Bajaj, P. H. Kreyns, and D. G. Franklin, The long range migration of hydrogen through Zircaloy in response to tensile and compressive stress gradients, Bettis Atomic Power Laboratory, Pittsburgh, PA, rep., 1998.

Neutron Radiography Setup

- Neutron radiography relies on the strong interaction between hydrogen and neutrons to create image contrast.[1]

[2]



Schematic of a neutron radiography set-up

- Neutrons pass through samples, are absorbed by a scintillator, emitting light, which is collected by film or a CCD camera.[1]
  - Image brightness is spatially resolved, based on the neutron beam.
  - The more neutrons that reach the scintillator, the brighter the image.

[1] N. L. Buitrago, J. R. Santisteban, A. Tartaglione, J. Marín, L. Barrow, M. R. Daymond, M. Schulz, M. Grosse, A. Tremsin, E. Lehmann, A. Kaestner, J. Kelleher, and S. Kabra, "Determination of very low concentrations of hydrogen in zirconium alloys by neutron imaging," Journal of Nuclear Materials, vol. 503, pp. 98–109, 2018.

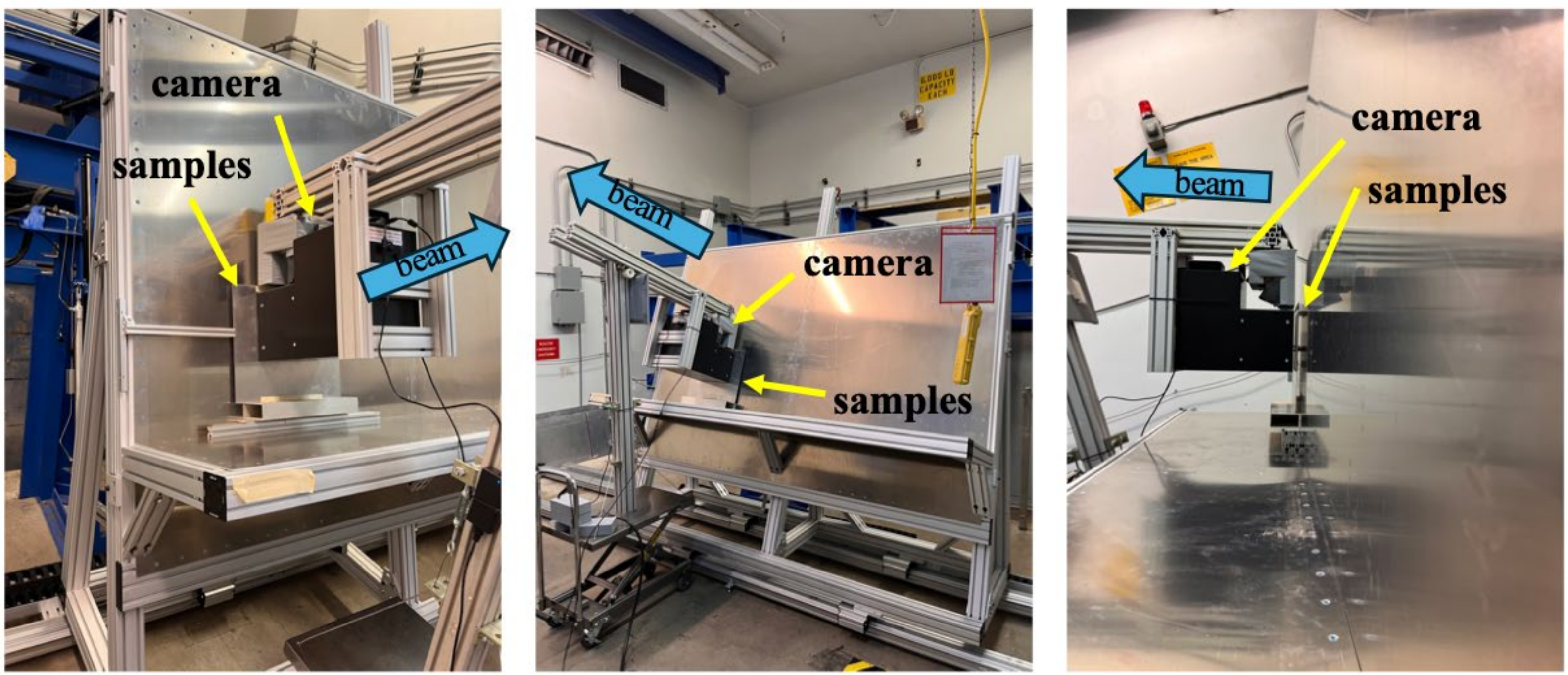
MRP Microreactor Program

Theory Versus Reality

- While the basic physics and concept of using NR as a quantitative technique as clear, several things make that challenging
  - Neutron beams are uncommon
    - Unfortunate events can eliminate availability
    - Pricing of replacements is inconsistent
  - Many of the available and affordable facilities are primarily focused on qualitative results
    - Is the wire connected?
    - Can we see the priming charge?
  - Imaging standards and practices to look at “shapes” are not what you would expect if you are looking at grey scales
    - Extracting data from grey scale images requires consistency and accounting for many variables
    - Reactor facilities are less consistent than you might think
    - “Basic” neutron cameras are largely targeted at rapid image acquisition for shape evaluation

Imaging Setup

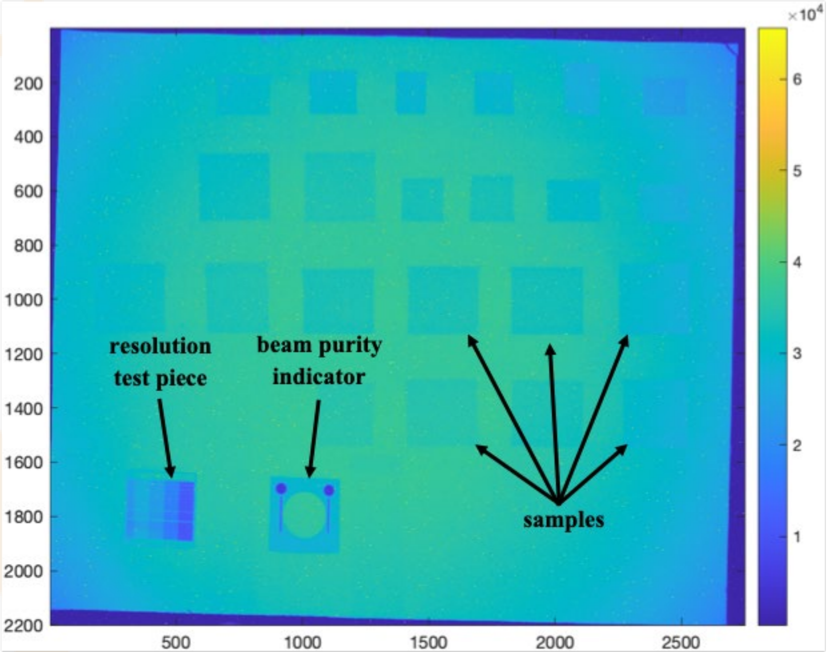
- After a few false starts, we moved the imaging work to the McClellan Nuclear Research Center (MNRC)
- The MNRC is a TRIGA reactor originally intended to image large aircraft parts for QA inspections

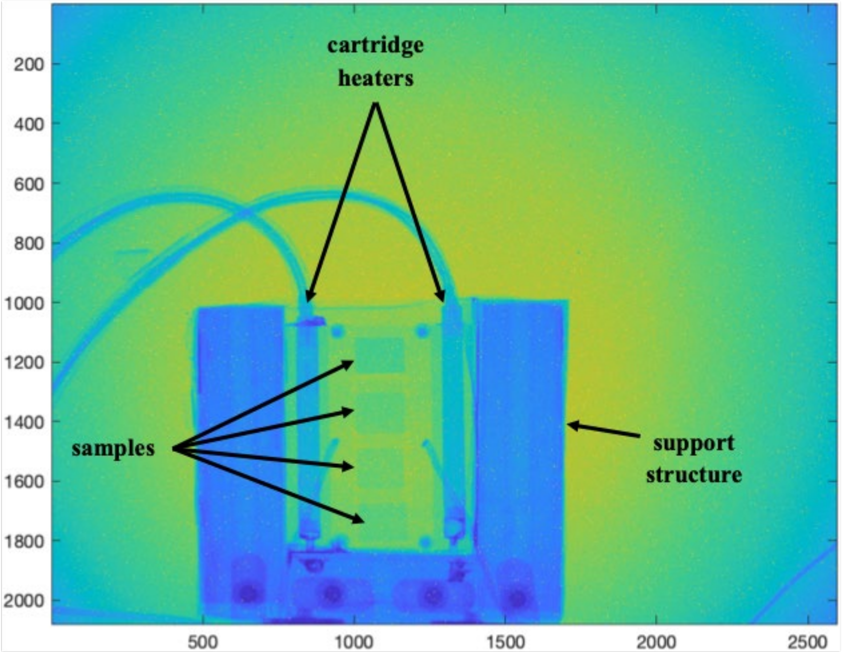


MRP Microreactor Program

Lens Effects (Vignetting)

- Images produced by the digital camera at the MNRC have a significantly non-uniform background field
- The vignette effects are similar in magnitude to the potential differences due to hydrogen concentration
- Correction requires more precision in camera/sample than currently possible

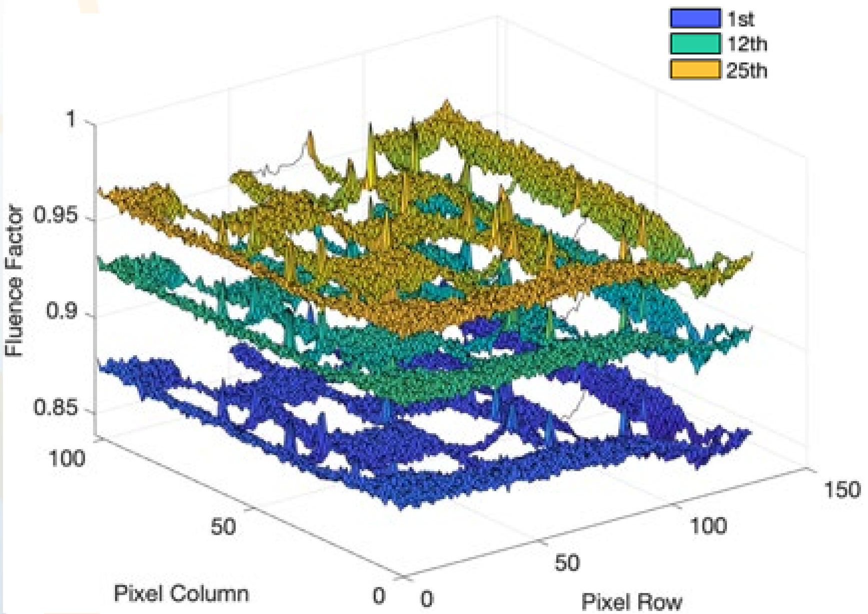


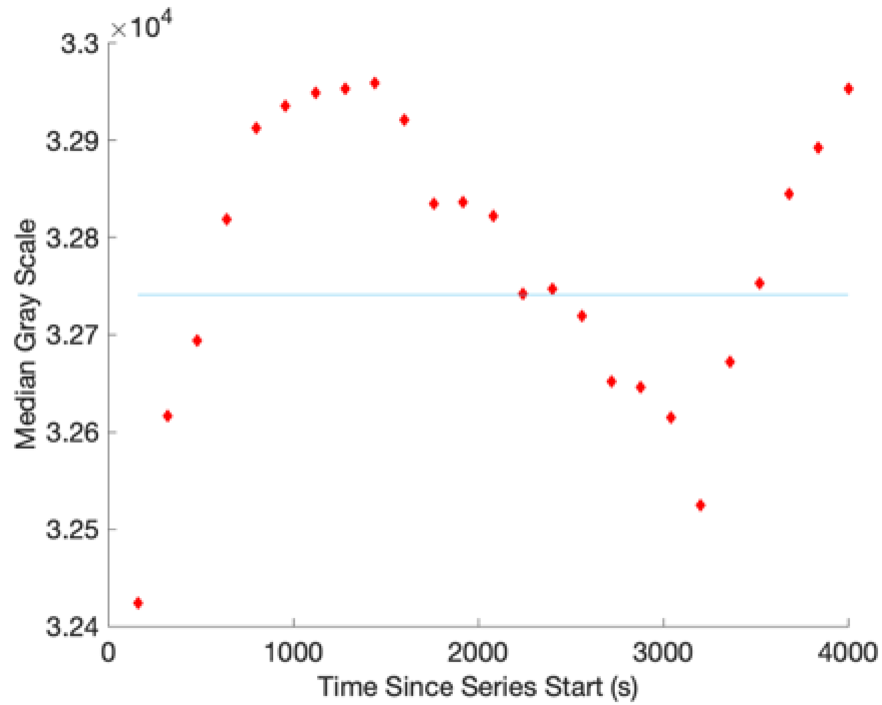


MRP Microreactor Program

Beam Variations

- Beam current in a reactor neutron beam is not constant
  - Relatively unimportant for many things
  - Extremely important for quantitative imaging





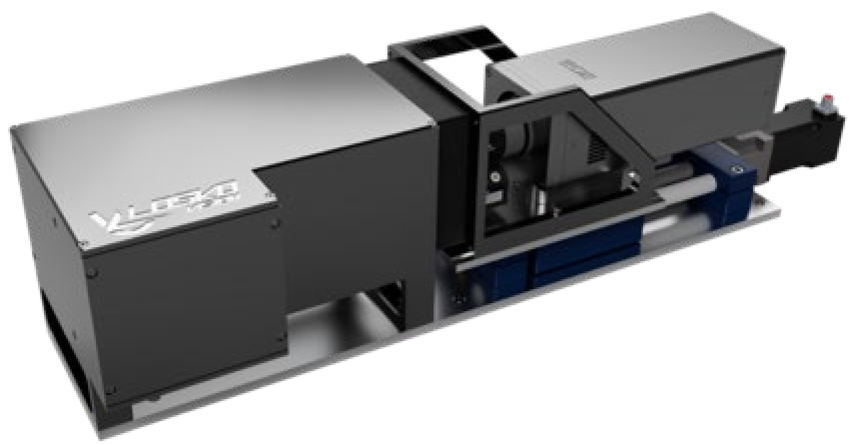
MRP Microreactor Program

Impacts

- These challenges (vignetting and beam variability) make it very unlikely that reproducible hydrogen concentration data can be extracted using a scintillator/CCD camera system as a reactor beam source
- However, recent advances in “Event Mode” imaging may provide an opportunity to overcome this

Event Mode Imaging

- Event Mode Imaging is a new technique for generating a neutron (or photon) image by discriminating and counting individual scintillator events
- Camera setup is similar to scintillator radiography cameras, but with a much faster, time dependent image sensor



Camera image from the Amsterdam Scientific Instruments web page (https://amscins.com/product/chronos-series/neutron-imaging/).

Event-Mode Imaging Schematic

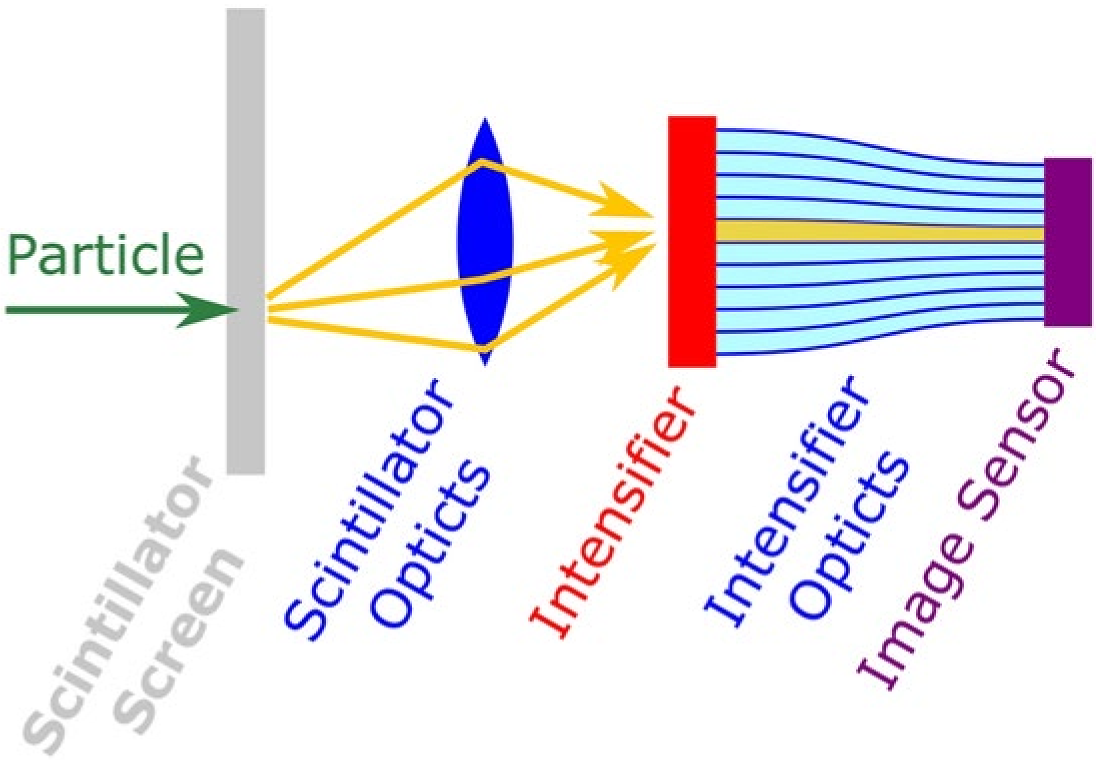
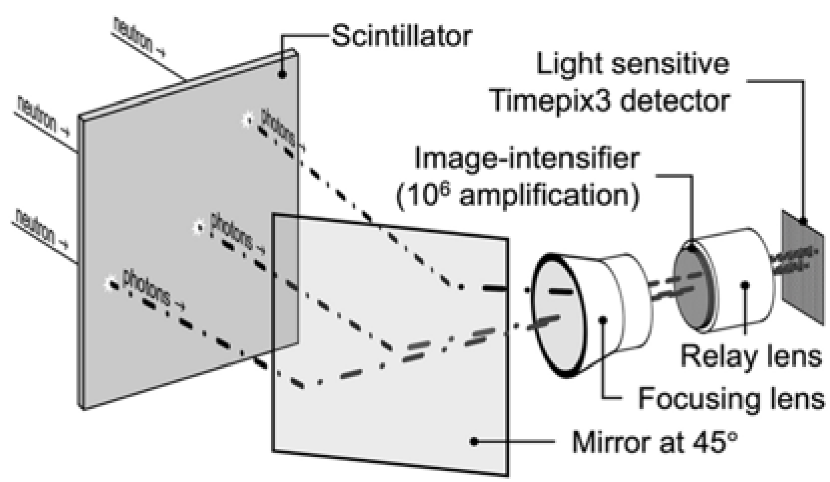


Image from: https://doi.org/10.1038/s41598-024-82095-2.

Event Mode Imaging Details

B) Schematic of the detector concept



C) Events on the detector using 15×15 cm² active area

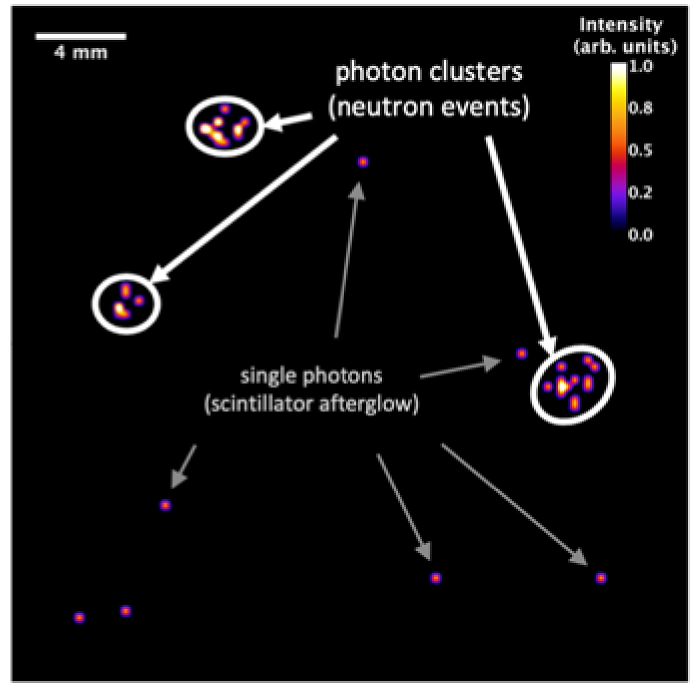


Image from: https://doi.org/10.1038/s41598-021-00822-5.

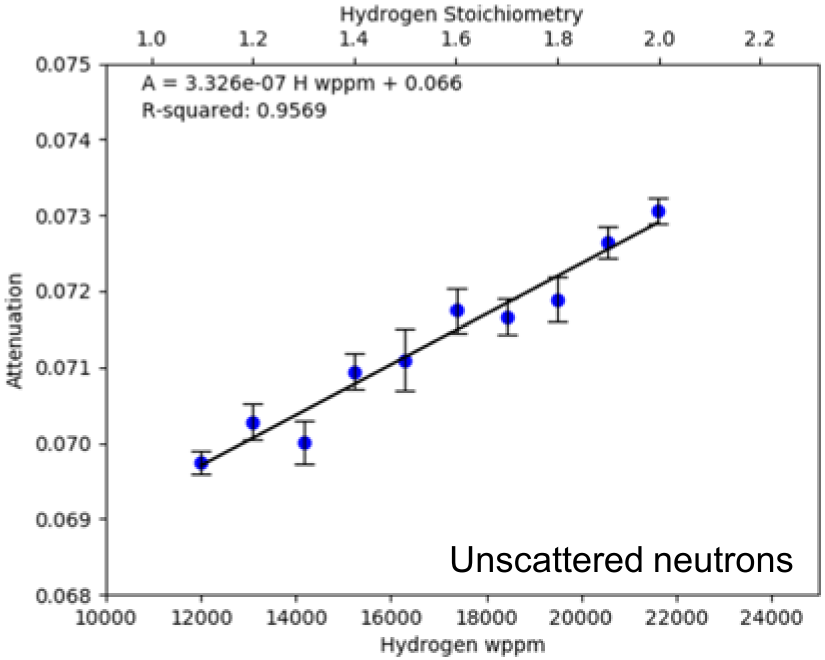
Opportunities

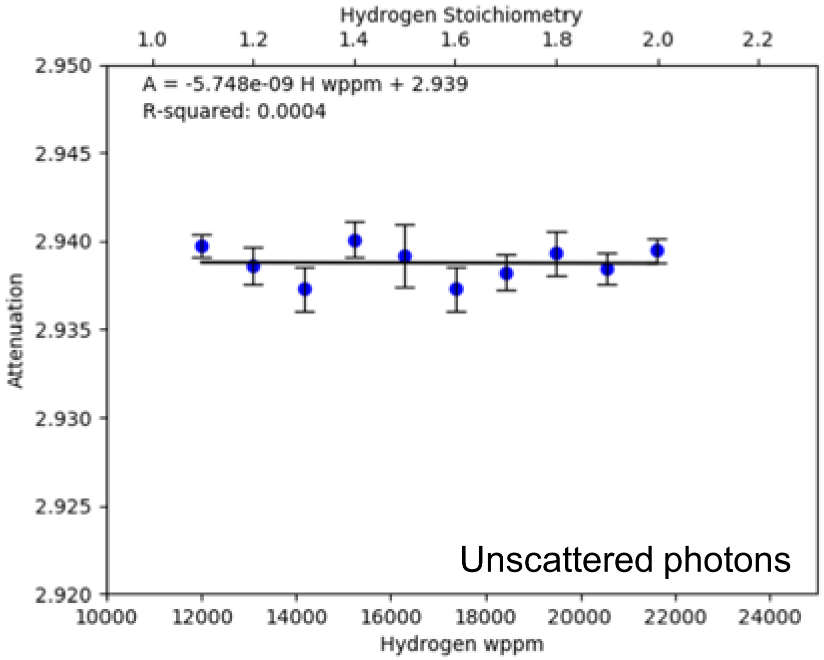
- Higher resolution
- Lower neutron fluence needed
- No (or minimal) lens effects
- Gamma vs neutron discrimination
- Gamma fluence as a neutron fluence reference

Challenges

- Requires processing of giga- to tera-bytes of data for each image
- Cameras are about an order of magnitude more expensive

Simulation: Neutron vs Gamma Attenuation





Thus, the photon data may provide a useful way to normalize for reactor power

MRP Microreactor Program

Final plans

- The final step in this project will be to attempt to demonstrate quantification of hydrogen concentration using event mode imaging at a reactor neutron source
- Planned for summer 2026

Questions?