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Optical Property Measurements in Neutrino Detection Media

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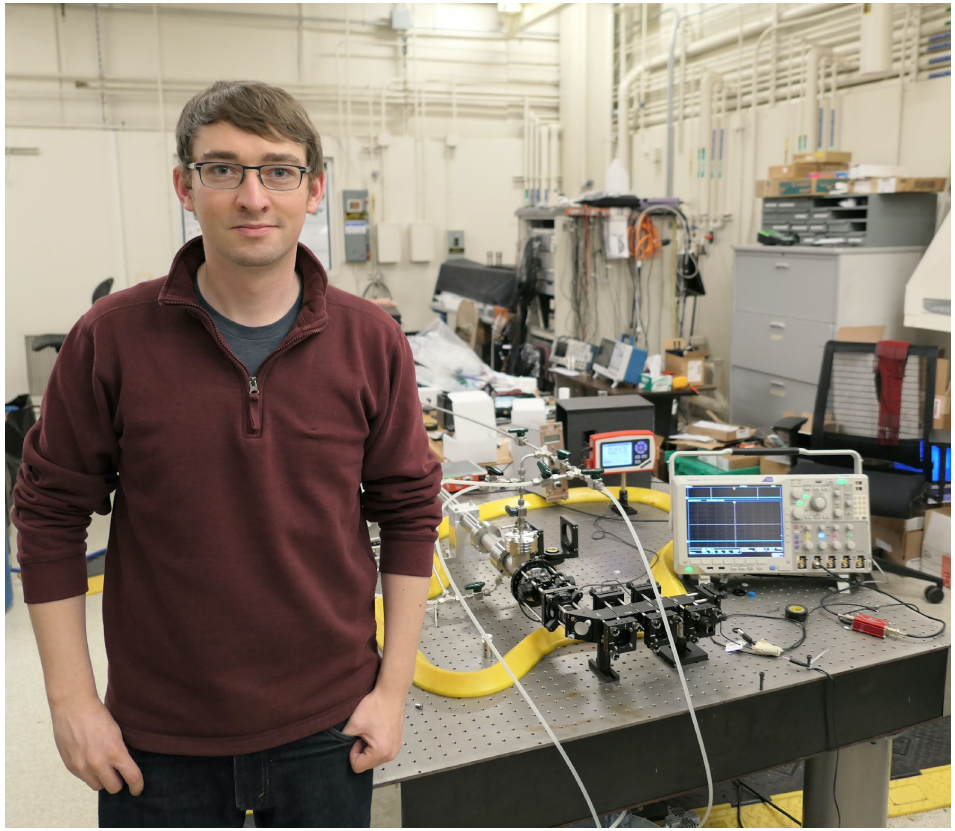
Introduction: Jake Hecla



Academic Advisor
Professor Kai Vetter
Dept. of Nuclear Engineering

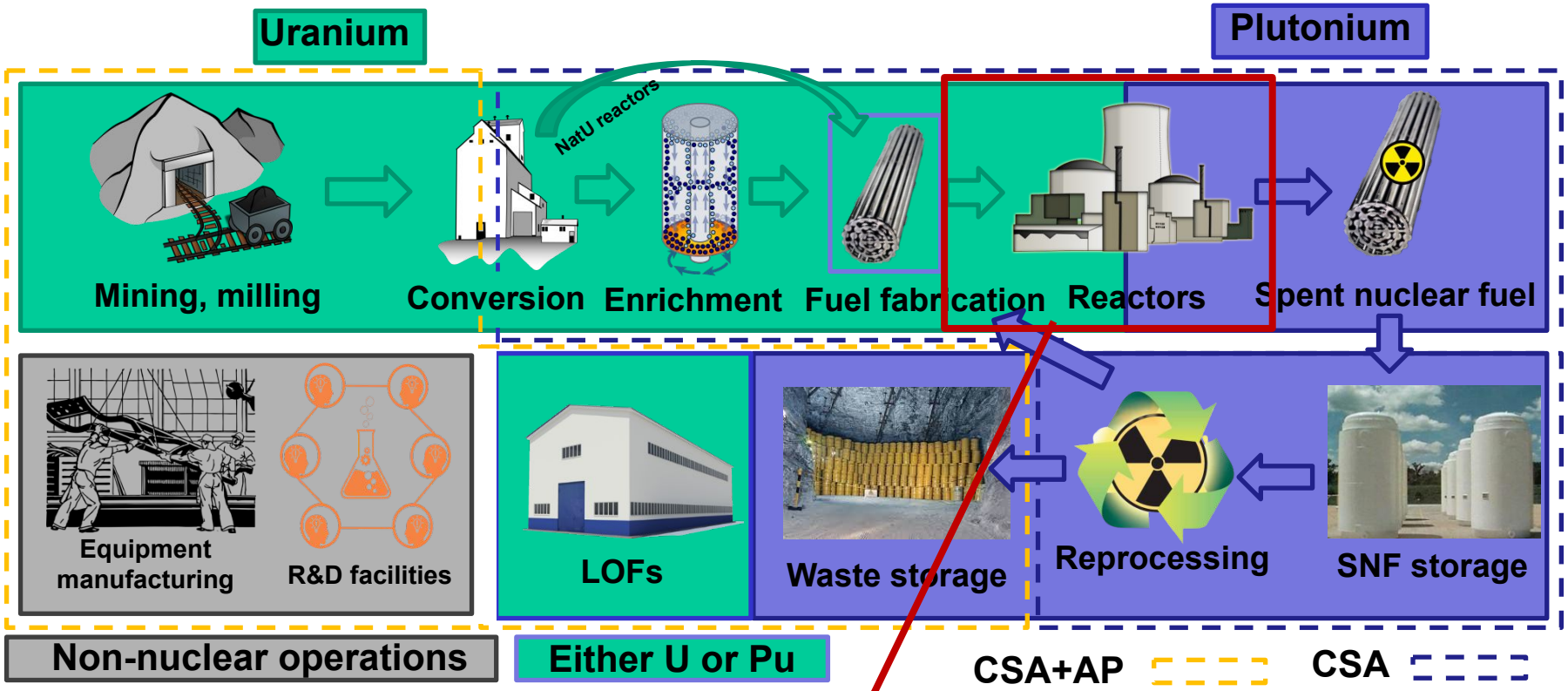
Lab Mentor
Dr. Adam Bernstein
Rare Event Detection Group

Focus: Radiation detection and nuclear instrumentation

Cross-cutting: Modeling and simulation

Project: Determination of optical properties of water-based liquid scintillator (WbLS) and other media in support of antineutrino detection for nonproliferation and safeguards applications

Background: ν –detectors have been proposed for reactor monitoring



Proposed applications from literature:

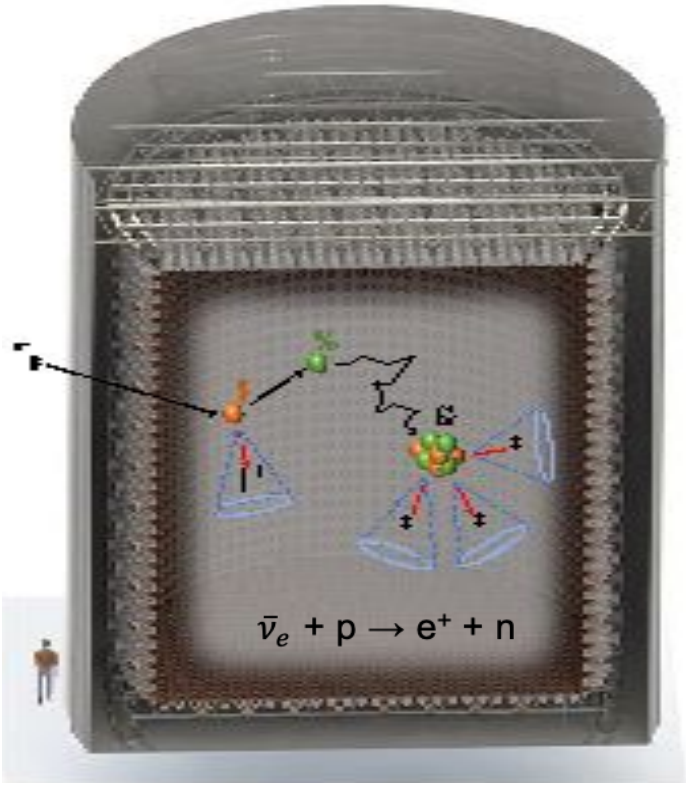
- Reactor power/fuel cycle monitoring
- Exclusion of undeclared reactors

Can a medium with a small scintillation component improve detector performance?

- Detection mechanism for (proposed) non-proliferation detectors is **inverse beta decay**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Correlated prompt and delayed signal
  - Positron Cherenkov cone
  - Delayed gamma cascade (8MeV in case of Gd) from radiative capture



- Scintillation light can aid in particle ID, improve event energy resolution can help separate signal from background,

→ Create material with small scintillation component

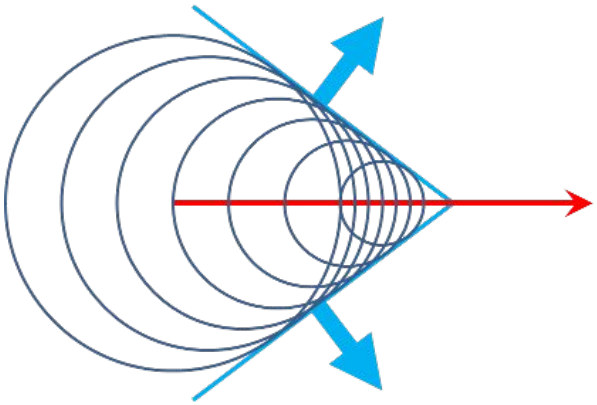
Gd improves IBD performance– but can energy/position/ID performance be improved with a few tens of photons per MeV scintillation yield?

Image credit: Minfeng Yeh, Brookhaven National Lab

What problem does WbLS solve?

- **LS: High light yield, short attenuation length**
  - High energy resolution, but directional information from Cherenkov lost
- **Water: low light yield, long attenuation length**
  - Good directional information (long attenuation length), but no light yield below Cherenkov threshold (.8MeV)

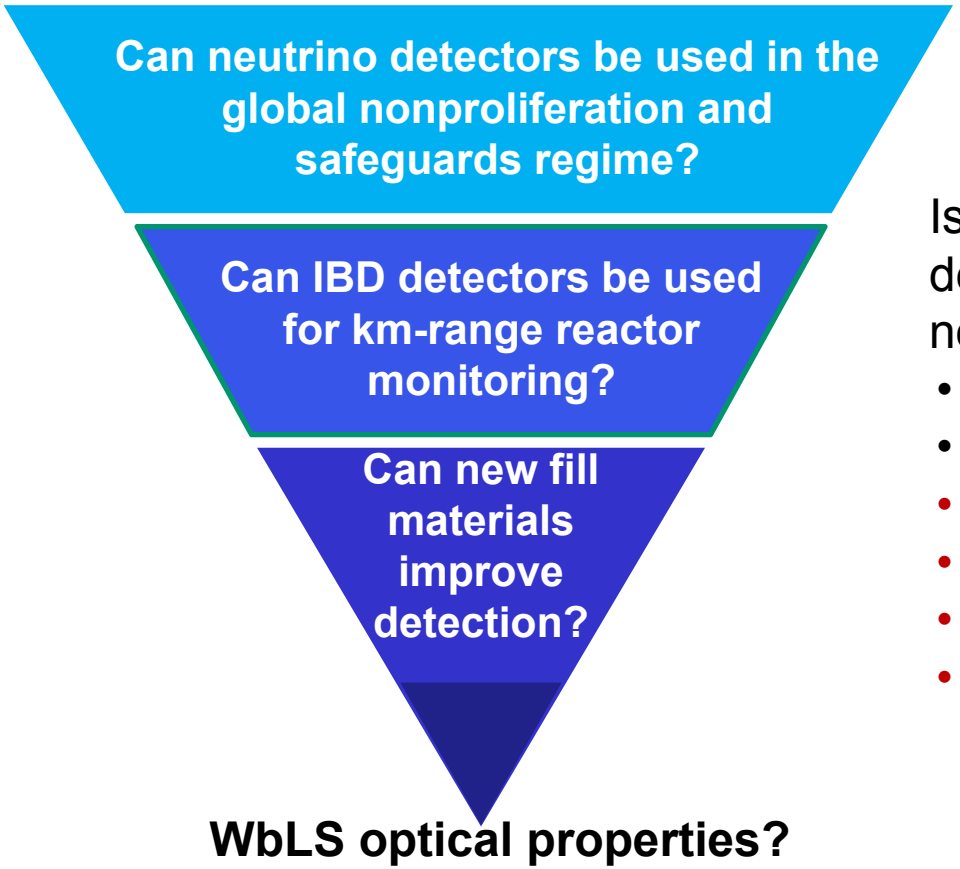
- **WbLS: Best of both worlds?**
  - Can resolve events below water's Cherenkov threshold while maintaining directional information—potentially revolutionary for rare event searches



Preservation of Cherenkov rings in a ~kT scale detector requires an attenuation length on the **order of 20m**

WbLS may meet this threshold and allow significant physics exploration below the Cherenkov threshold

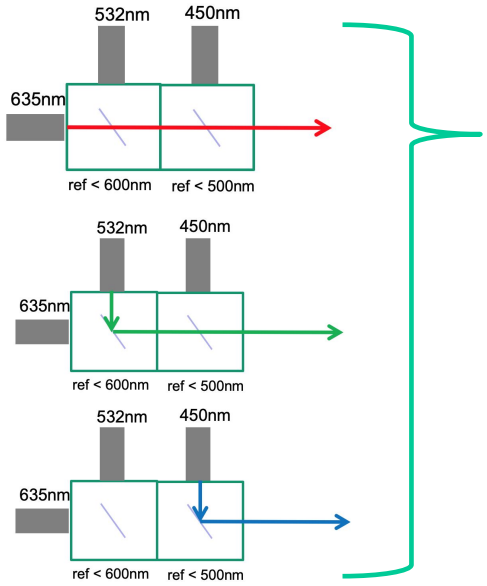
WbLS optical property measurements are key to realizing nonproliferation monitoring goals

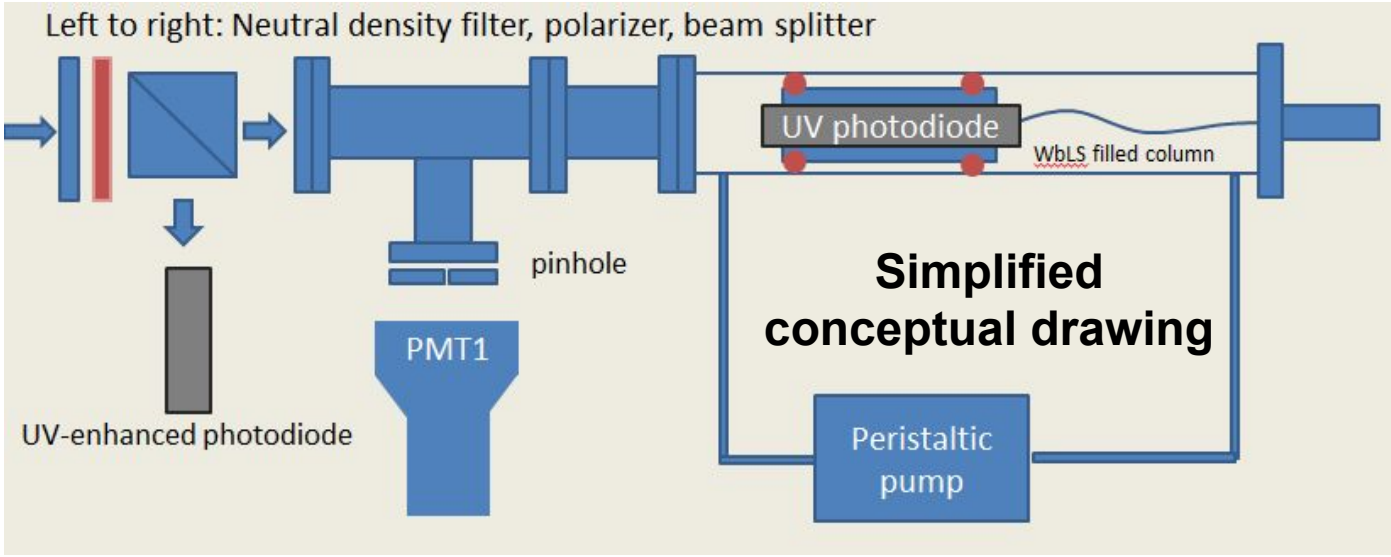


Is WbLS suitable for neutrino detectors useful for nuclear nonproliferation efforts?

- Light yield (LBNL) ✓
- Stability (BNL) ✓
- Optical attenuation
- Scattering
- Polarization-dependent effects
- Aging

Sealed, adjustable beamline concept avoids pitfalls of vertical column and integrating cavity systems



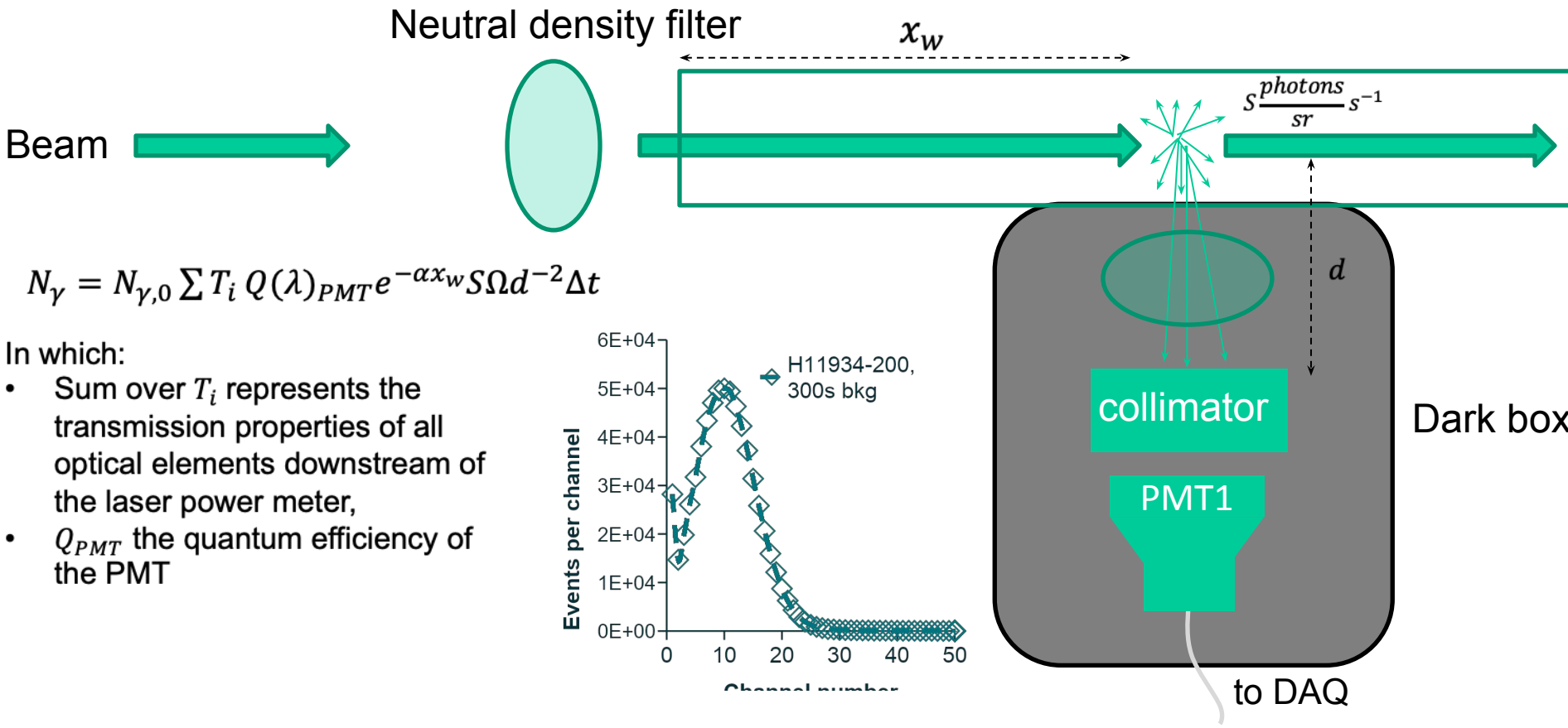


- Fluid under test is used as working fluid to move optical mount via pressure provided by peristaltic pump
- Dichroic beam combiner allows selection of wavelength without changes to optics

Design advantages

- Simultaneous attenuation/scatter measurement possible
- No fluid/gas interface in optical path
- Optical alignment is simple, durable

Scattering measurements can be performed simultaneously using a collimated compact PMT

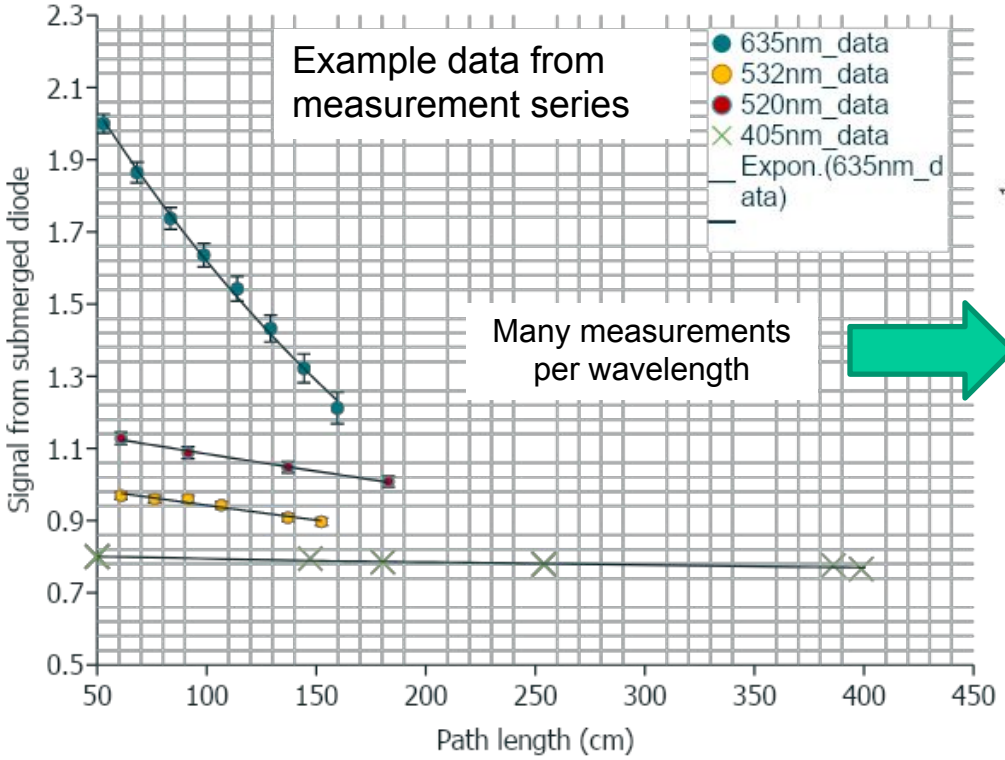


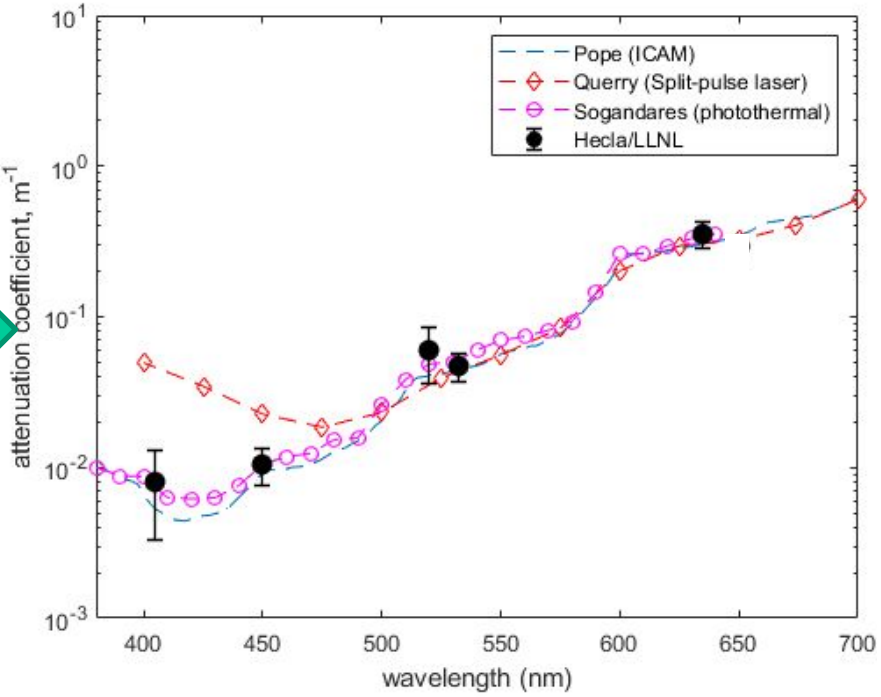
$$N_\gamma = N_{\gamma,0} \sum T_i \, Q(\lambda)_{PMT} e^{-\alpha x_w} S \Omega d^{-2} \Delta t$$

In which:

- Sum over T_i represents the transmission properties of all optical elements downstream of the laser power meter,
- Q_{PMT} the quantum efficiency of the PMT

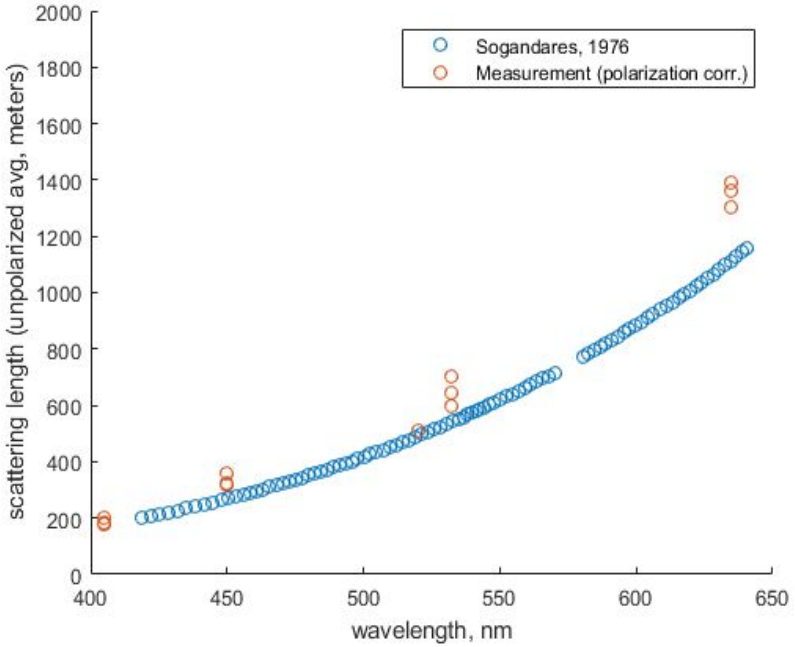
DI water attenuation measurements compare favorably with world-class metrology experiments





Absorption measurements in DI water compare favorably with world-class metrology experiments

DI water scattering measurements compare favorably with theory



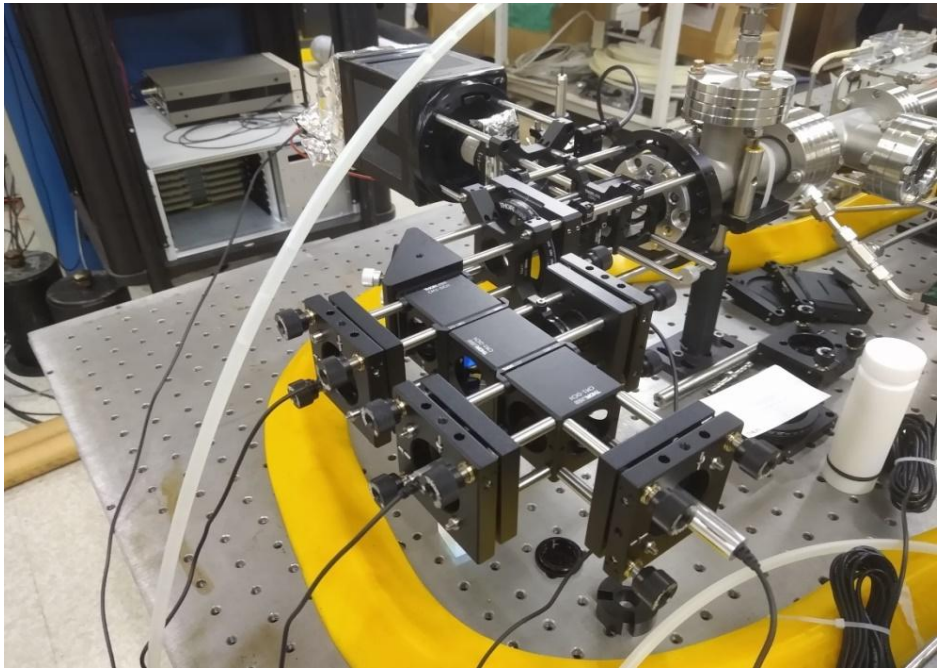
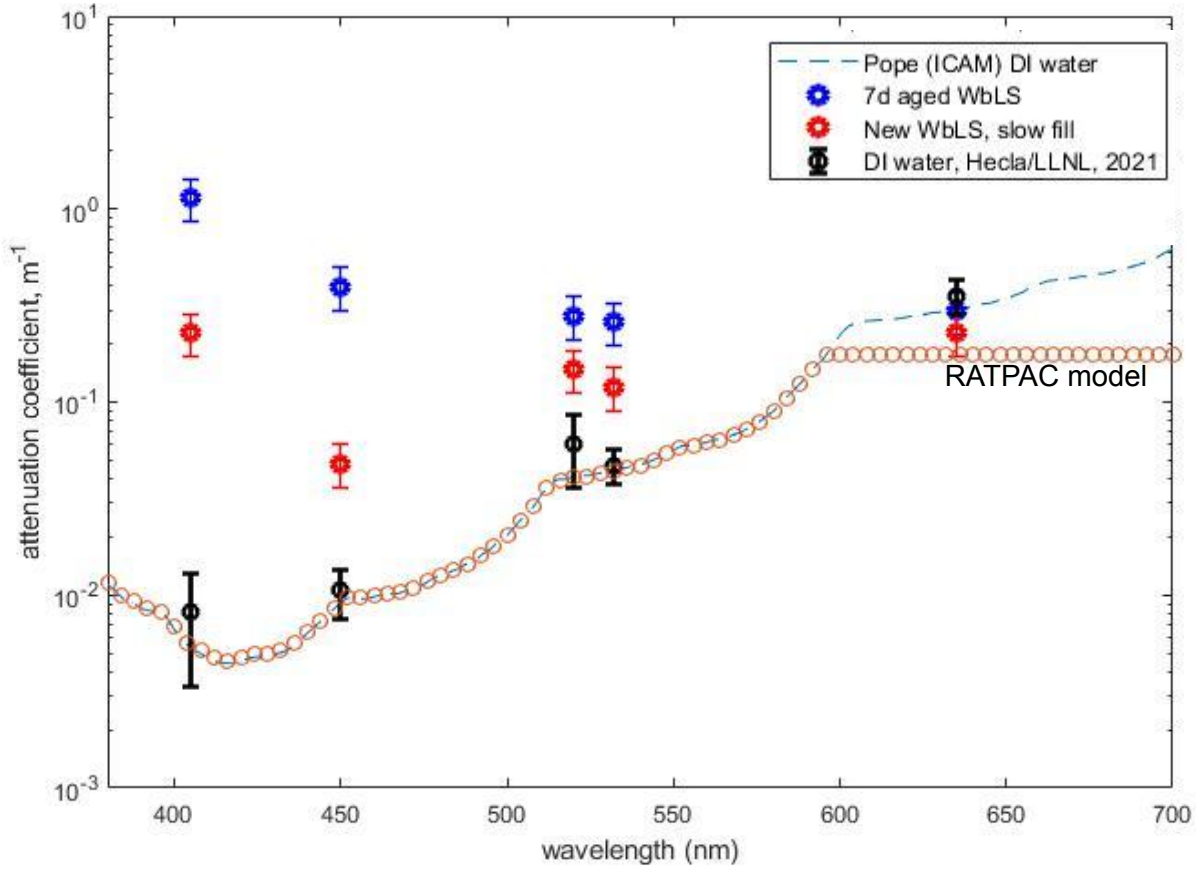


Fig.1: Direct measurements of the 90-degree scattering cross-section for vertically polarized show excellent agreement with theory. *Example dataset shown with multiple measurements conducted over ~2h.*

Gd-WbLS measurements

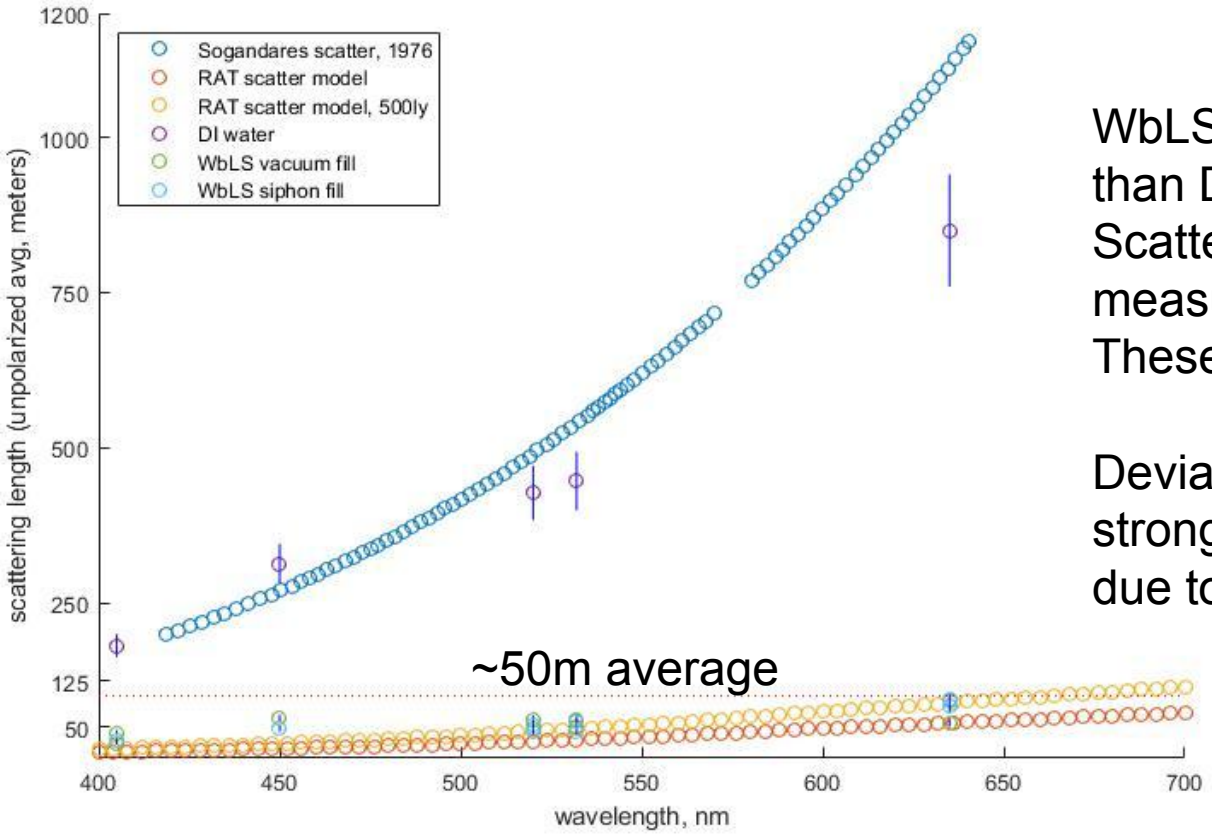
Gd-WbLS attenuates visible light *significantly* more than DI water



WbLS attenuates significantly more than shown in the RATPAC model.

Degradation of WbLS attenuation parameters was observed after seven days in the system under argon cover gas.

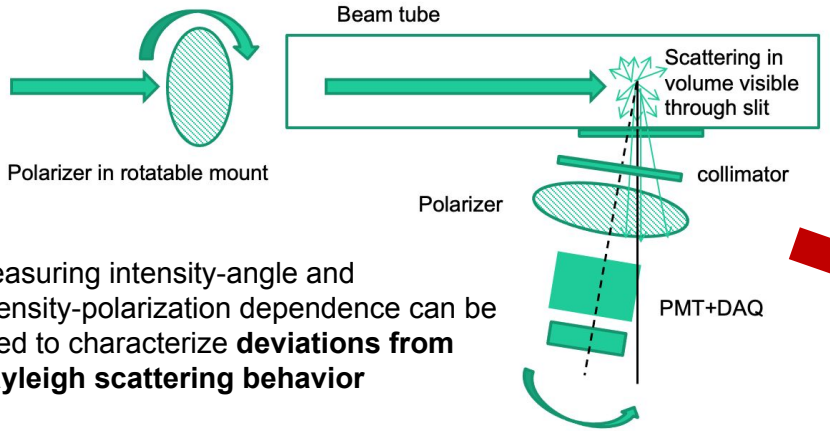
Gd-WbLS scatters more than water, but less than current RATPAC model



WbLS is a much stronger scatterer than DI water, as expected. Scattering behavior was not measured with respect to aging. These tests are ongoing.

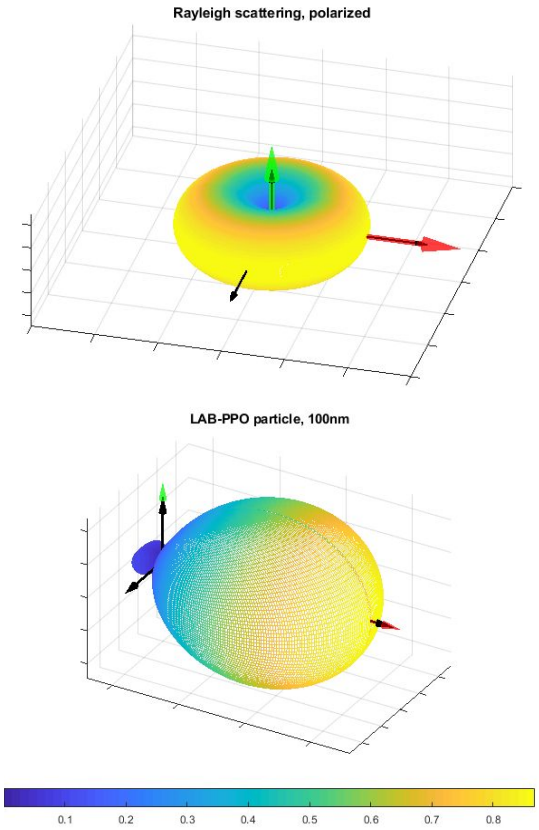
Deviation from the model is strongest at 450nm, which may be due to a systematic error

Scattering components (Rayleigh, Mie) can be separated based on differential cross sections



Measuring intensity-angle and intensity-polarization dependence can be used to characterize **deviations from Rayleigh scattering behavior**

Pivoting, rotating PMT and polarizer allow sampling of differential xs

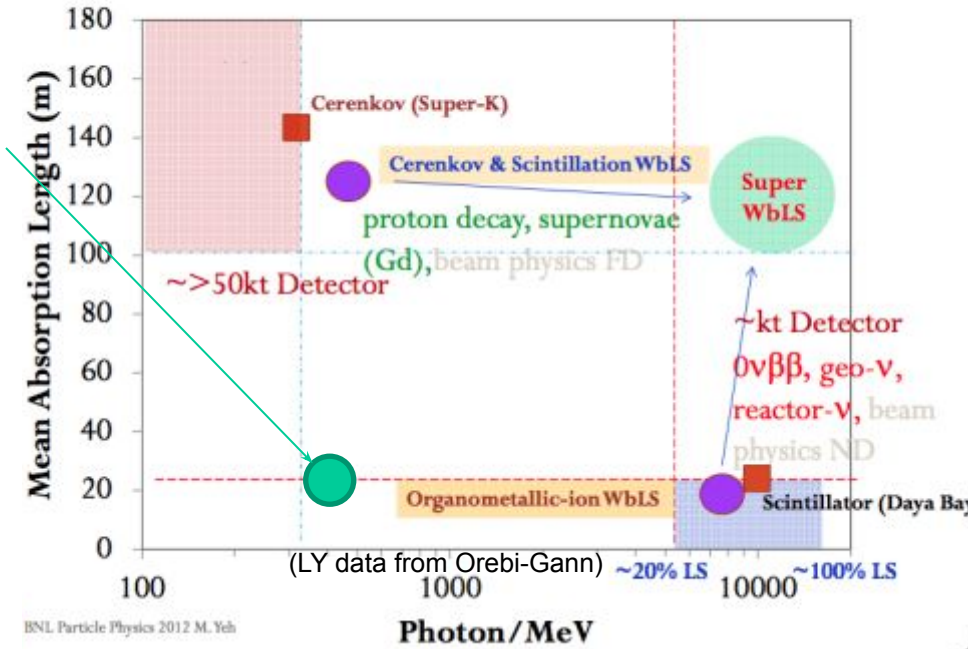


- **Concept:** Rayleigh and Mie scattering components have dramatically different phase functions
- Determination of phase function can be performed *while* measuring attenuation/scatter coefficient, assuring consistency for a given sample
- Work in progress ☺

Gd-WbLS Initial Conclusions

- **Gd-WbLS has a *longer* scattering length than modeled**
- **Gd-WbLS has a *shorter* attenuation length than modeled**
- **Degradation of attenuation length is evident in ~days**

- **Continuing investigation**
  - More data points for aging likely useful
  - Adding more wavelength coverage
  - Angle and polarization dependent scatter measurements ongoing



NON-LLNL Work

WAR ON THE ROCKS National security. For insiders. By insiders. RUSSO-UKRAINIAN WAR ABOUT SIGN IN BECOME A MEMBER TEXAS NATIONAL SECURITY REVIEW

MOBILE NUCLEAR POWER REACTORS WON'T SOLVE THE ARMY'S ENERGY PROBLEMS

JAKE HECLA
COMMENTARY

DECEMBER 14, 2021

I

Minimizing the consequences of nuclear accidents through effective communication

By Jake Hecla, Gabriela Levikow, Ksenia Pirnavskaia | Nuclear Energy, Voices of Tomorrow

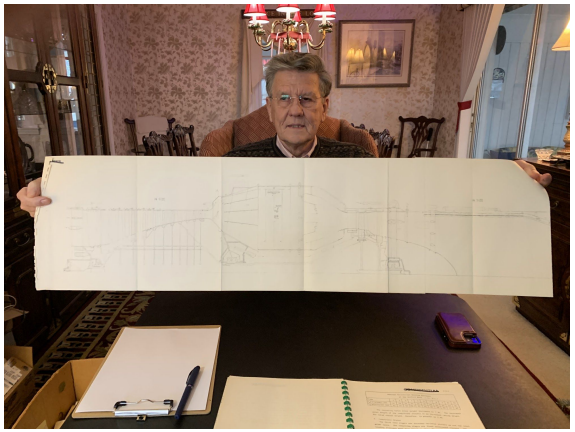
II

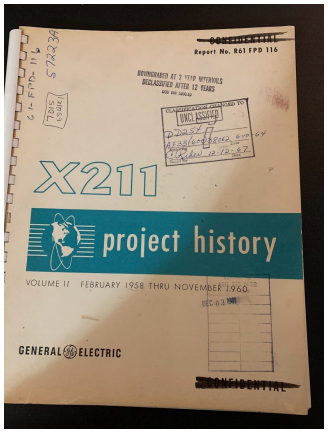
As tensions mount on Ukraine's borders, it's time to understand what led to the INF Treaty's demise

By Aaron J. Berliner, Jake Hecla, Michael Bondin, Austin Mullen, Elena Osorio Camacena, Alex Droster, Dinara Ermakova, Tyler Scott Nagel, Nicole L. Nappi, Katherine J. Oosterbaan, Sarah R. Stevenson, Chelsea D. Willett, Eric F. Matthews, Manseok Lee, Karl van Bibber, Michael Nacht | Nuclear Risk, Nuclear Weapons, Opinion, Voices of Tomorrow

***War on the Rocks* Commentary:** Analyzes unresolved technical questions about *Project Pele* related to fuel damage, intended deployment modalities and cost projections. Additionally quoted in *Military Times* article on 4/15/22 on mobile reactor technology.

***The Bulletin of the Atomic Scientists* Papers:**
I) Suggests nuclear risk communication strategies based on "correlates of risk," analyzes role of citizen-science groups in risk perception
II) Explores Russian INF violations, discusses technical roadblocks to developing INF-like agreements in the future





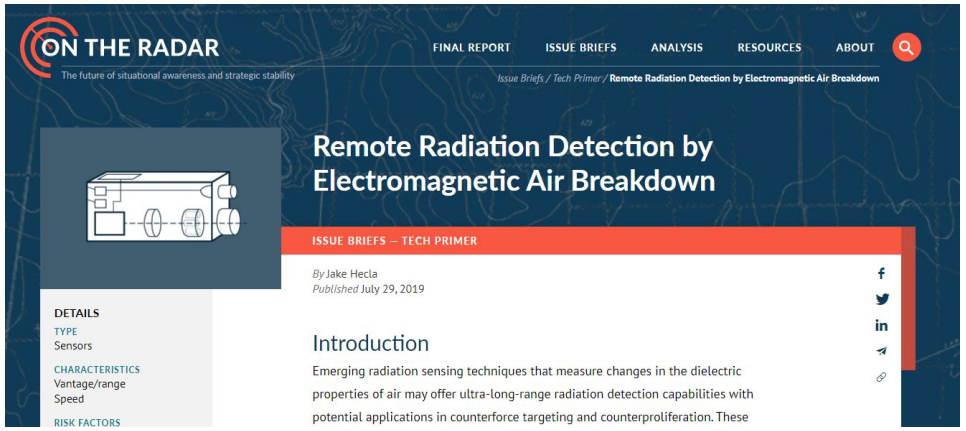
Nuclear aircraft propulsion document preservation: Personal effort to find and digitize remaining documents from US Aircraft Nuclear Propulsion program. Left: The *original* hand-drawn sketch of the XNJ140 nuclear turbojet. Right: X211 nuclear turbojet internal history document. Both in the collection of David Carpenter, retired GE company historian

NSSC Experience

Public Policy and Nuclear Threats (PPNT) 2018: Established links with CISAC and CSIS, began working with Sig Hecker's international nuclear forum program

Meeting in Beijing with Stanford center affiliates to discuss verification technologies, November 2019.

- NSSC created connections with LLNL, opened doors to CISAC and supported my professional development through PPNT



CSIS Tech primer written with the Berkeley Nuclear Policy Working Group (NPWG) on a novel radiation detection technique

Acknowledgements

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