U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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Irradiation of Optical Components of In-Situ Laser Spectroscopic Sensors for Advanced Nuclear Reactor Systems

Advanced Sensors and Instrumentation Annual Webinar

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University of Michigan

Project Overview

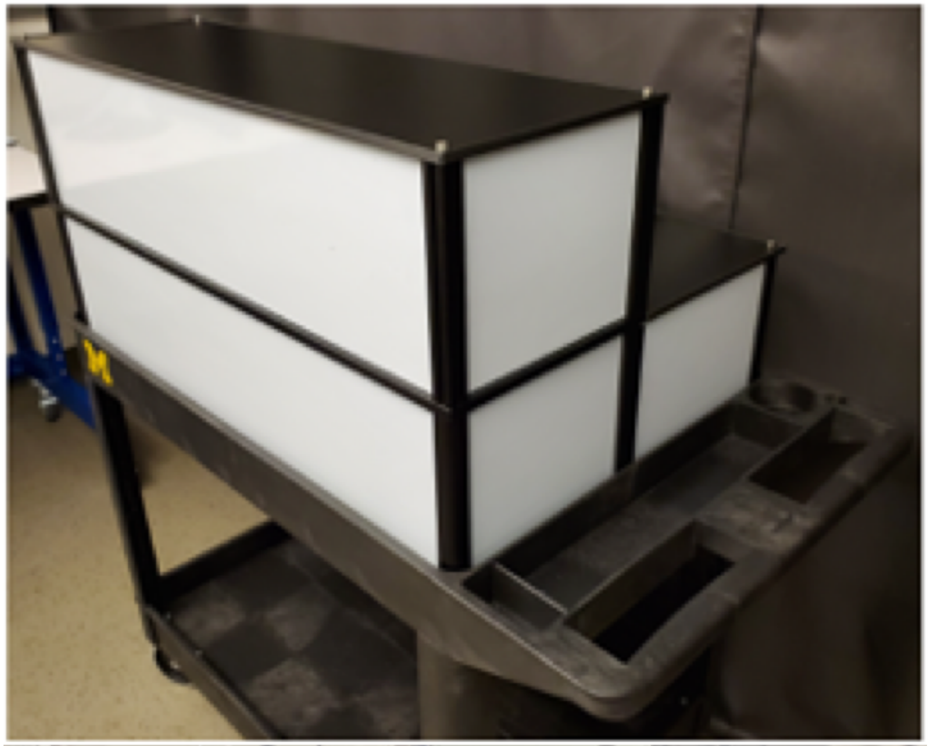
- Goal and Objective: understand the effect of optical damage on the performance of optical spectroscopic sensors: (1) nonlinear refractive index; (2) transient radiation-induced absorption; (3) concurrent optical damage and thermal annealing
- Participants: Igor Jovanovic, Bryan Morgan, Milos Burger, Piyush Sabharwall (INL), Paul Marotta (MicroNuclear), Lei Cao (OSU-NRL: NSUF)
- Schedule:
  - Year 1: Procure samples; develop mobile PIE system
  - Year 2: Evaluate neutron activation; construct and test heating setup; conduct gamma irradiation with post-heating
  - Year 3: Conduct neutron irradiation with post-heating
  - Year 4: Conduct gamma and neutron irradiation with concurrent heating

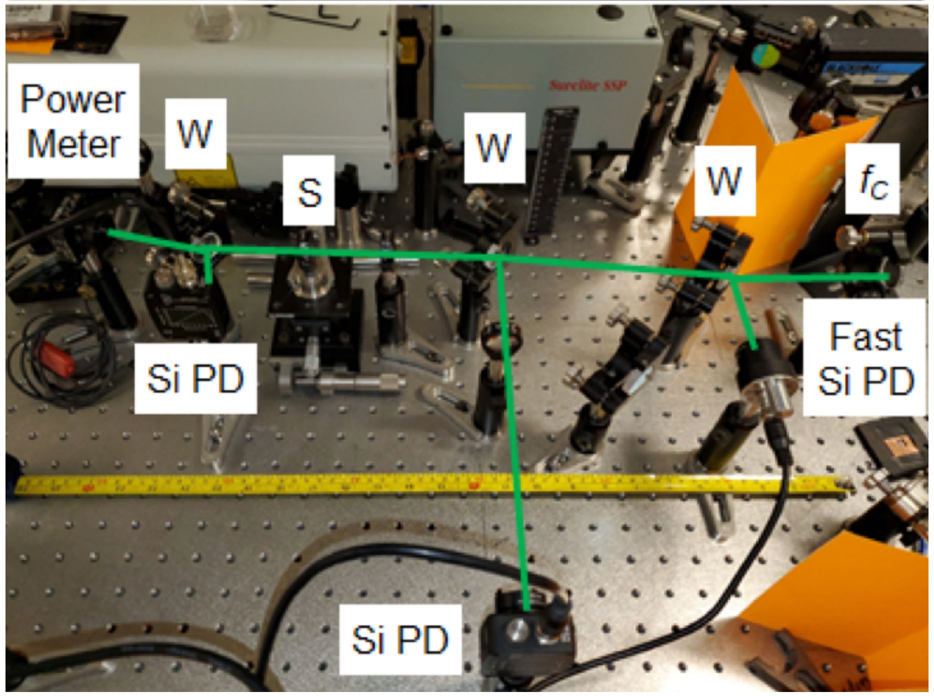
MicroNuclear LLC

Summary of Accomplishments

<u>FY 2020 Accomplishments:</u>

- Test samples specified and procured
- Mobile PIE system designed
- PIE setup linear spectroscopy constructed and validated
- Z-scan proof-of-concept constructed and under test
- Interfaced with NSUF (OSU) to design and construct the sample furnace



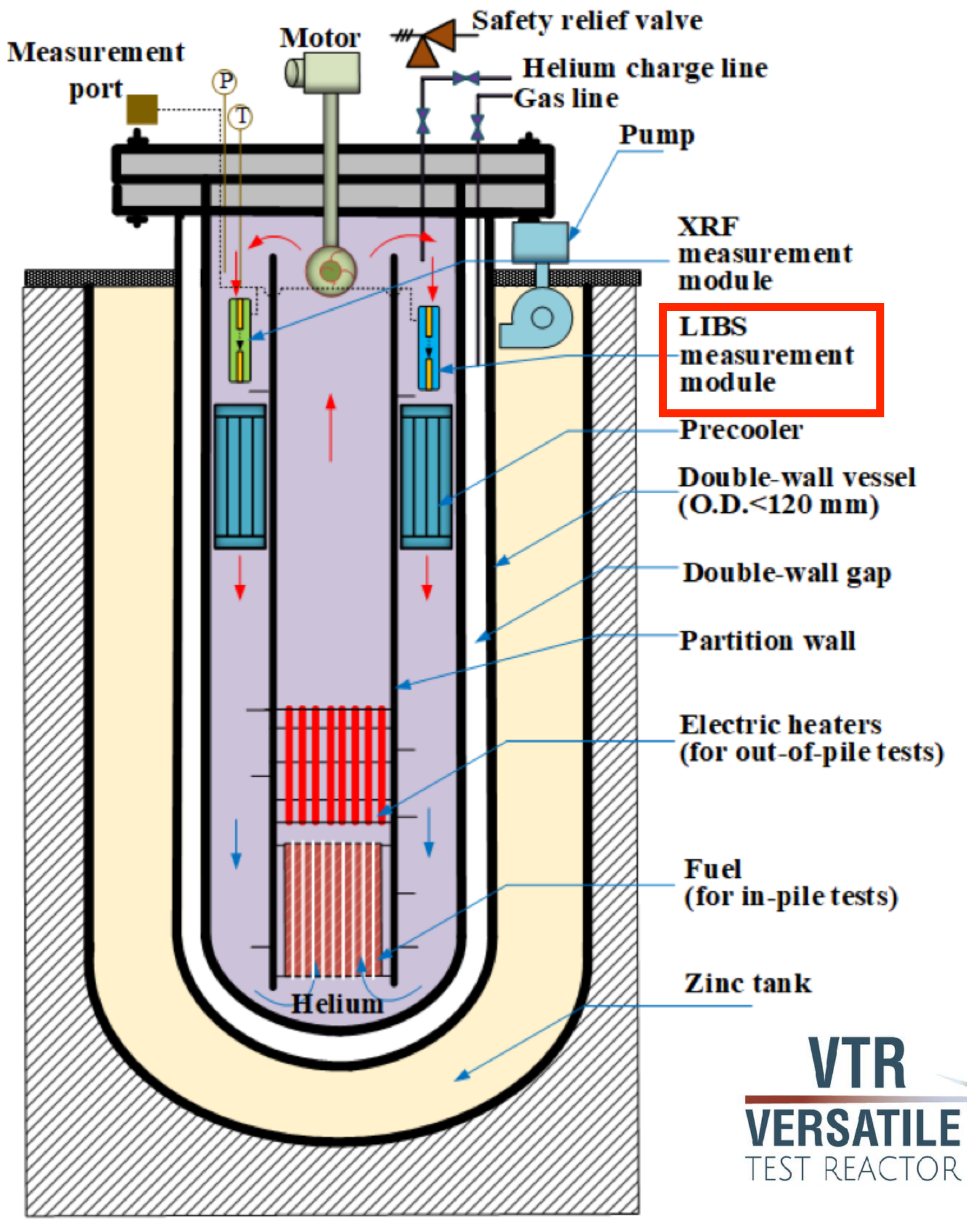


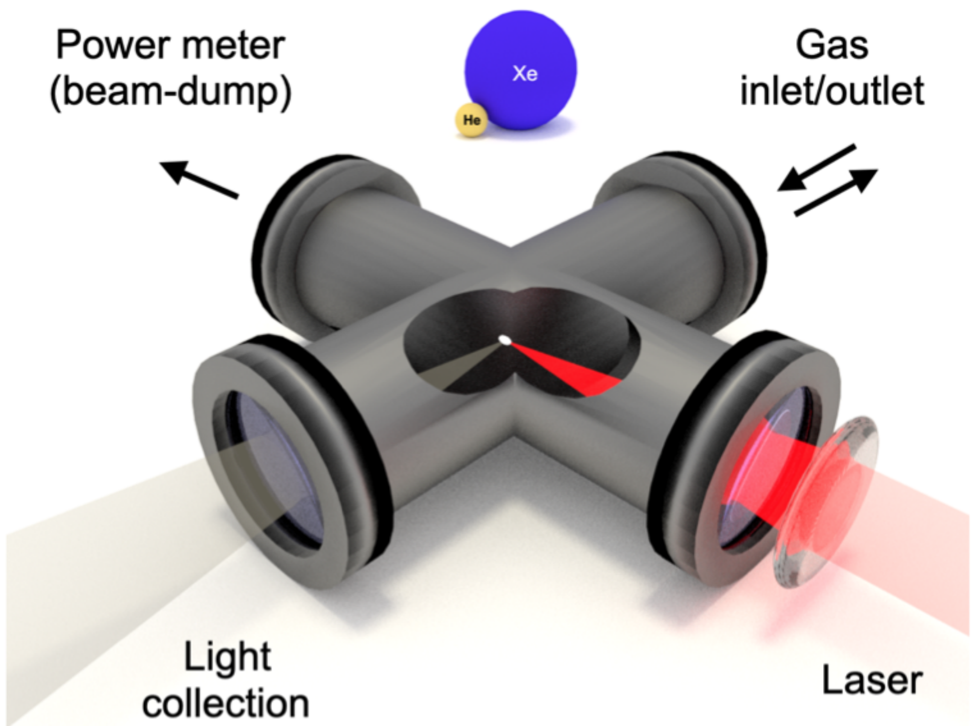
Technology Impact

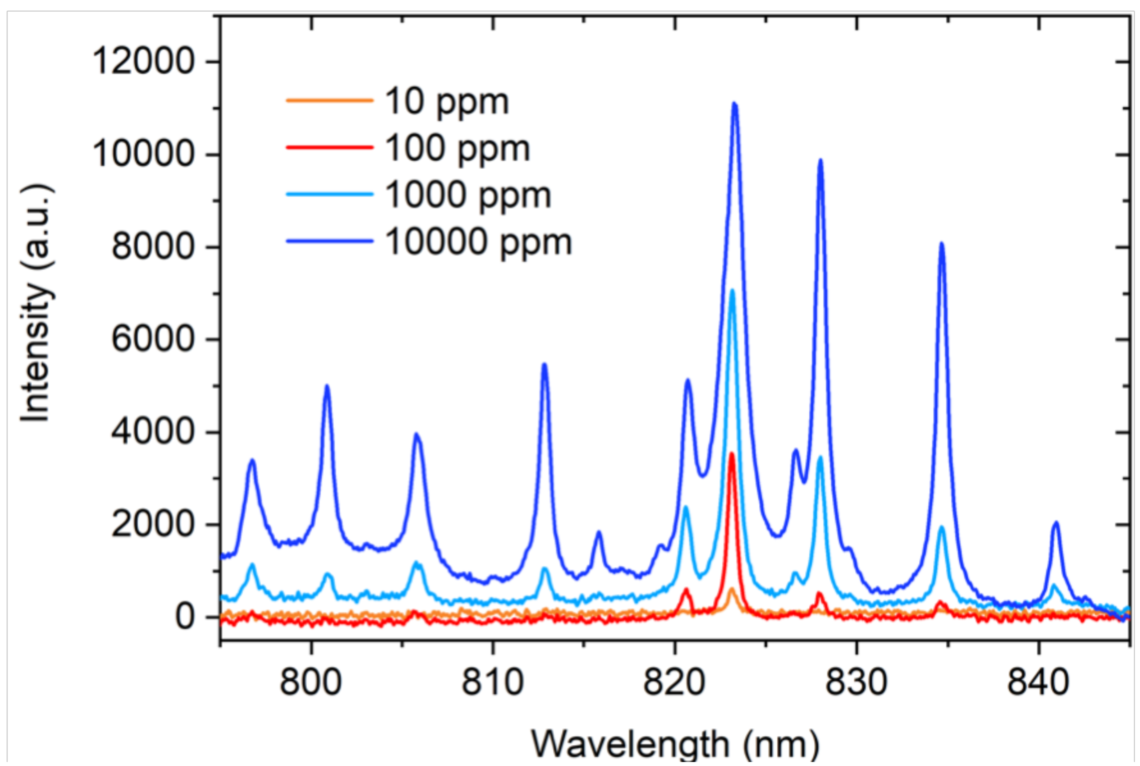
- Real-time, *in-situ* measurements of important operational parameters in advanced nuclear systems
- Optical instrumentation can be subjected to challenging environments: radiation, temperature, pressure, limited access
- Develop an improved understanding of radiation damage in optical materials <u>in conditions relevant for their operation in real-time optical sensors</u>
- First-ever attempt to quantify the effect of irradiation on nonlinear optical properties of materials
- **Cross-cutting impact: design and concept of operation of a wide range of optical instrumentation for nuclear applications**
- Integration with nuclear technology corporate partner to develop preliminary concept for deployment

Example of Active Optical Sensing: Versatile Test Reactor (VTR)

- Advance the safety of future GCFRs by measuring the primary coolant purity level *in situ*
- Detect fission gases (Xe, Kr), fuel cladding failure (Si), and other impurities (U, Ag, …) in He coolant

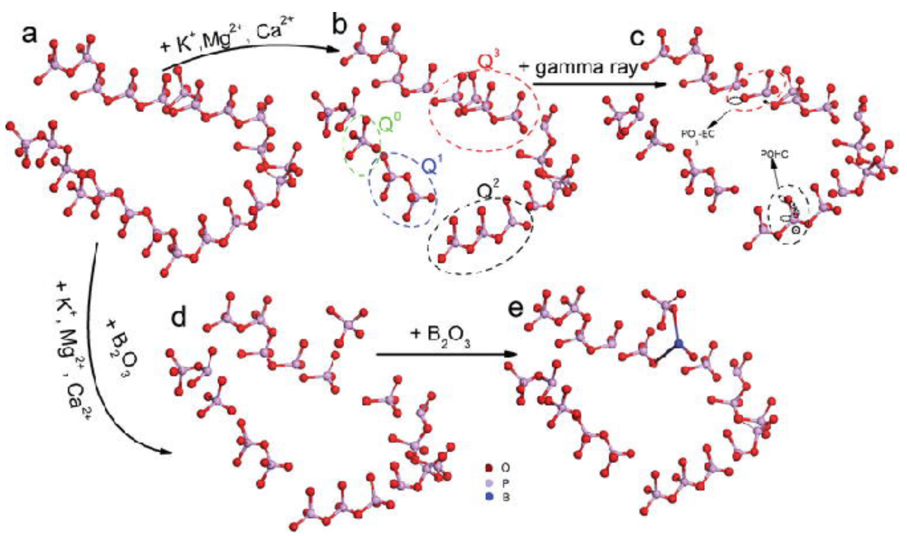




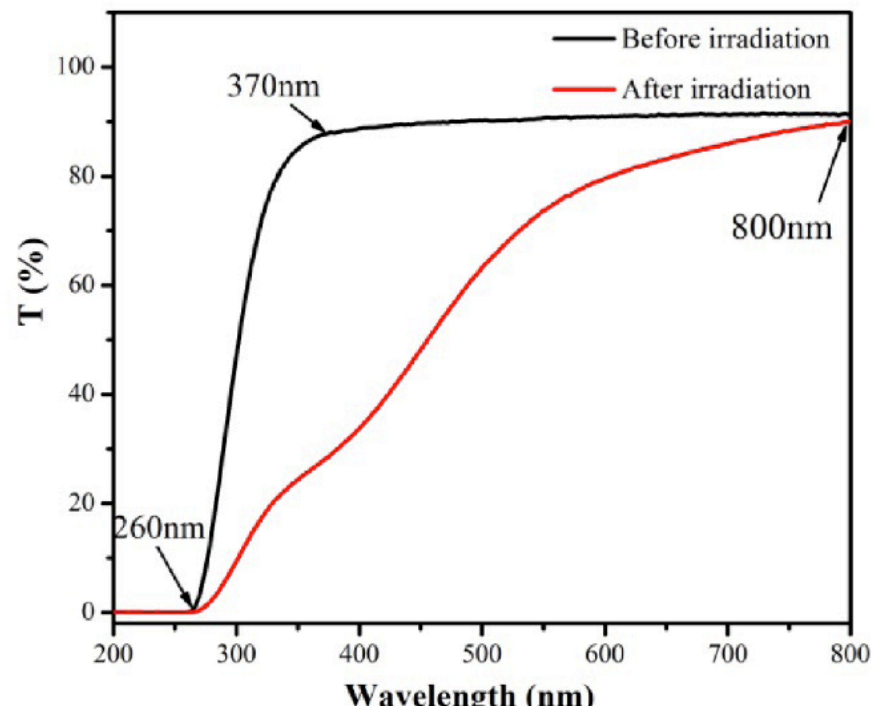


Radiation Damage of Optical Materials

- Optical modification when exposed to ionizing radiation.
- On the atomic scale, these changes are usually referred to as defects.



He et al. 2017 Optics Materials Express



Chen et al. 2016 Optics Express

Irradiation can change color of glass

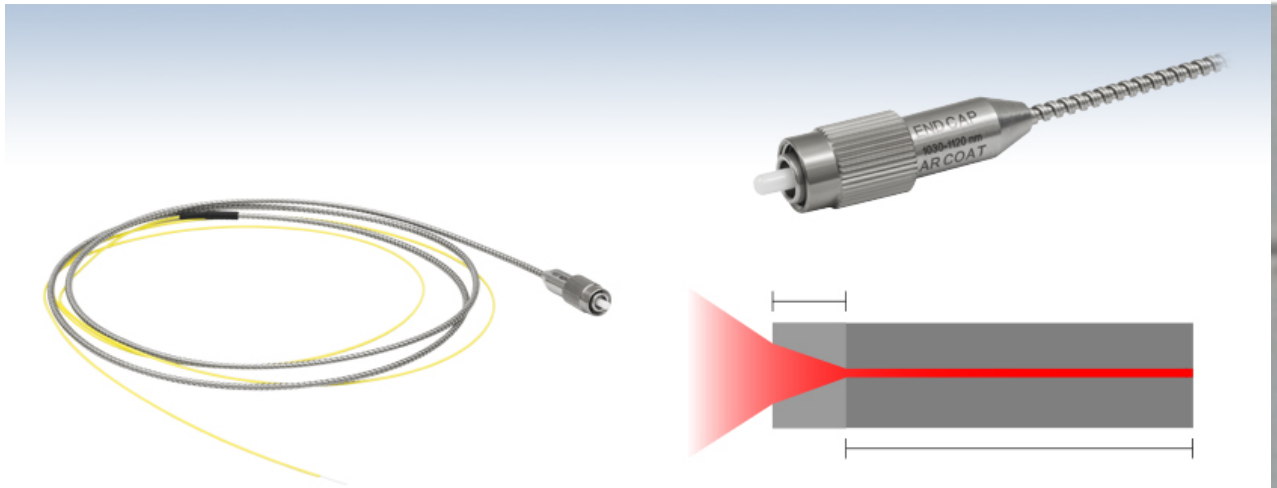
https://www.realorrepro.com/article/Irradiation-Changes-Color-of-Glass

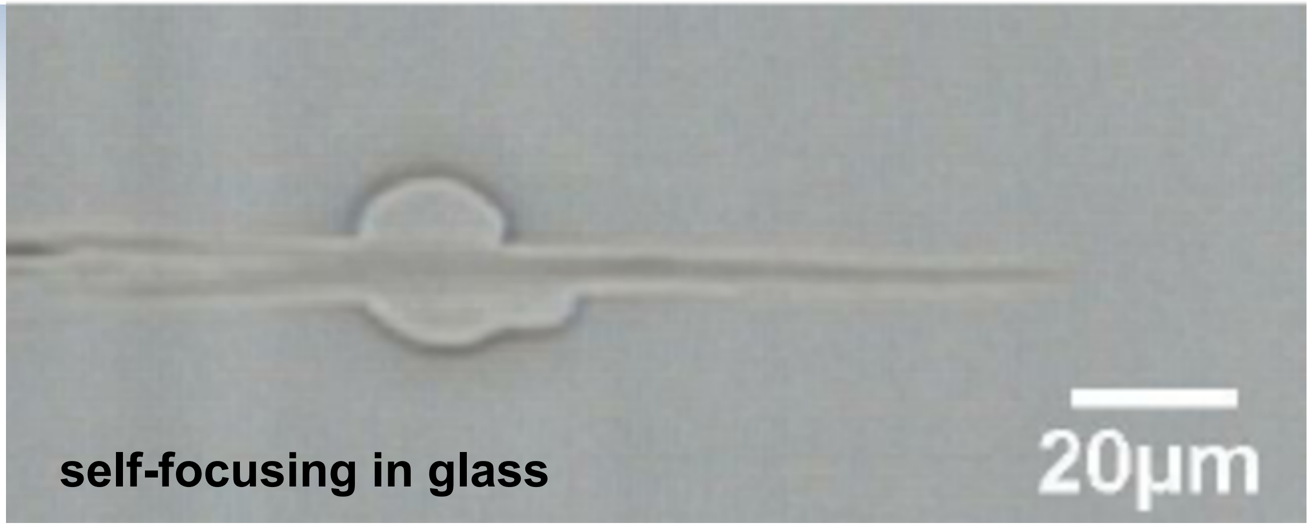
Chemical Approach to Glass, M.B. Volf, Elsevier

- Knock-on and ionization process as damage mechanisms
- The loss of electron: trapped electrons, trapped holes, ruptured Si-O bonds and non bridging oxygen ions
- Radiation-Induced Attenuation (RIA); Radiation-Induced Emission (RIE); refractive index changes

Gaps in Understanding of Radiation Damage in Optical Materials

- Transient dependence of optical damage
- Simultaneous optical damage and annealing, which is much closer to conditions that may be encountered in nuclear power systems
- Effect of irradiation on the nonlinear refractive index and absorption
- Coupled spectral-temporal evolution of the resulting optical characteristics





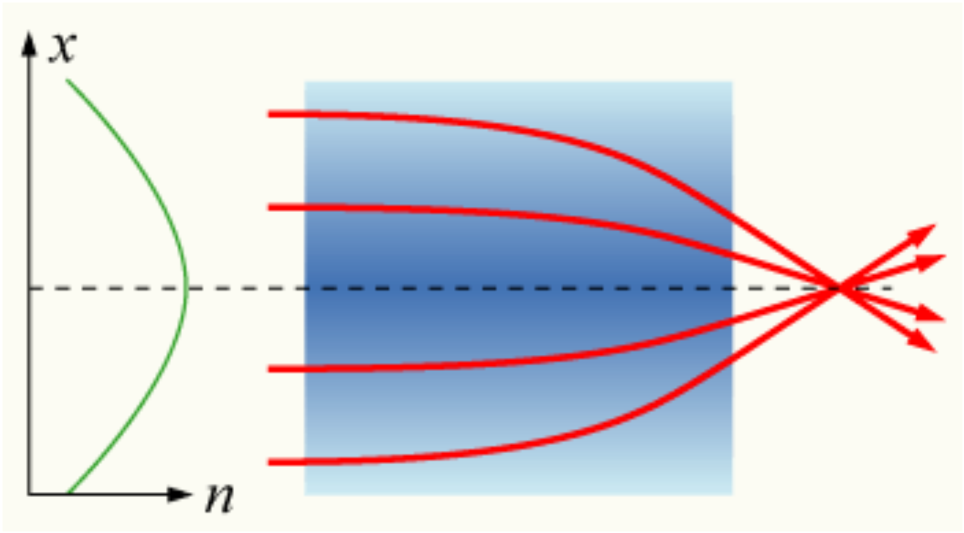
self-focusing in glass

Nonlinear Optical Effects

- Nonlinear behavior of a material is reflected in its intensity-dependent change of optical absorption, reflectivity, refractive index, etc.

$$P = \epsilon_0 \chi^{(1)} E + \epsilon_0 \chi^{(2)} E^2 + \epsilon_0 \chi^{(3)} E^3 + \ldots$$

- The third-order nonlinear susceptibility leads to processes such as third-harmonic generation, two-photon absorption, and the intensity-dependent refractive index.



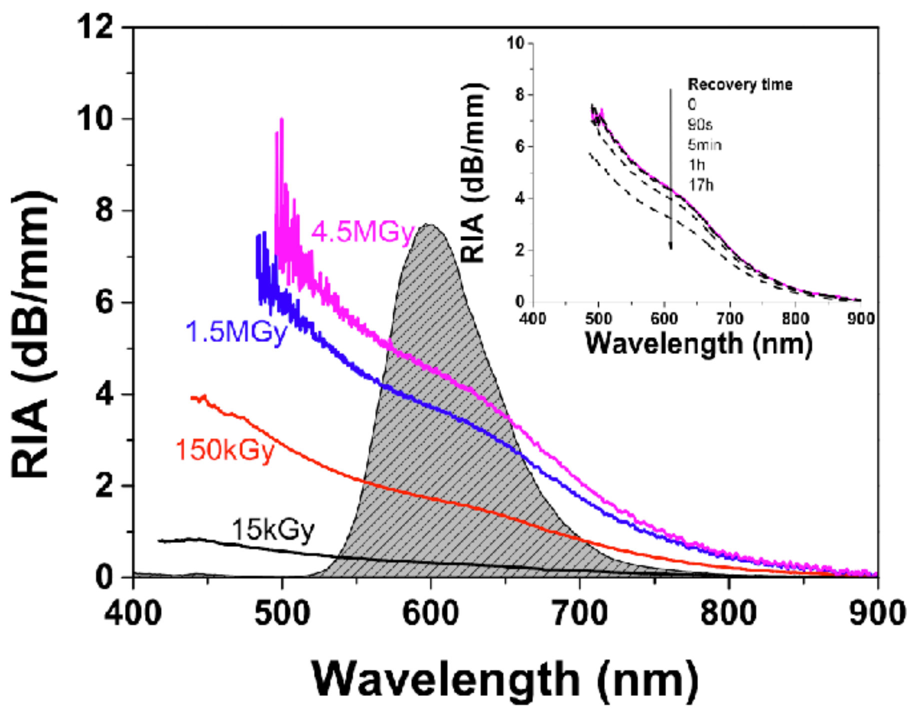
$$n = n_0 + n_2 I$$ { Self-focusing / Nonlinear absorption

$$n_2 = \frac{12\pi^2 \chi^{(3)}}{n_0^2}$$

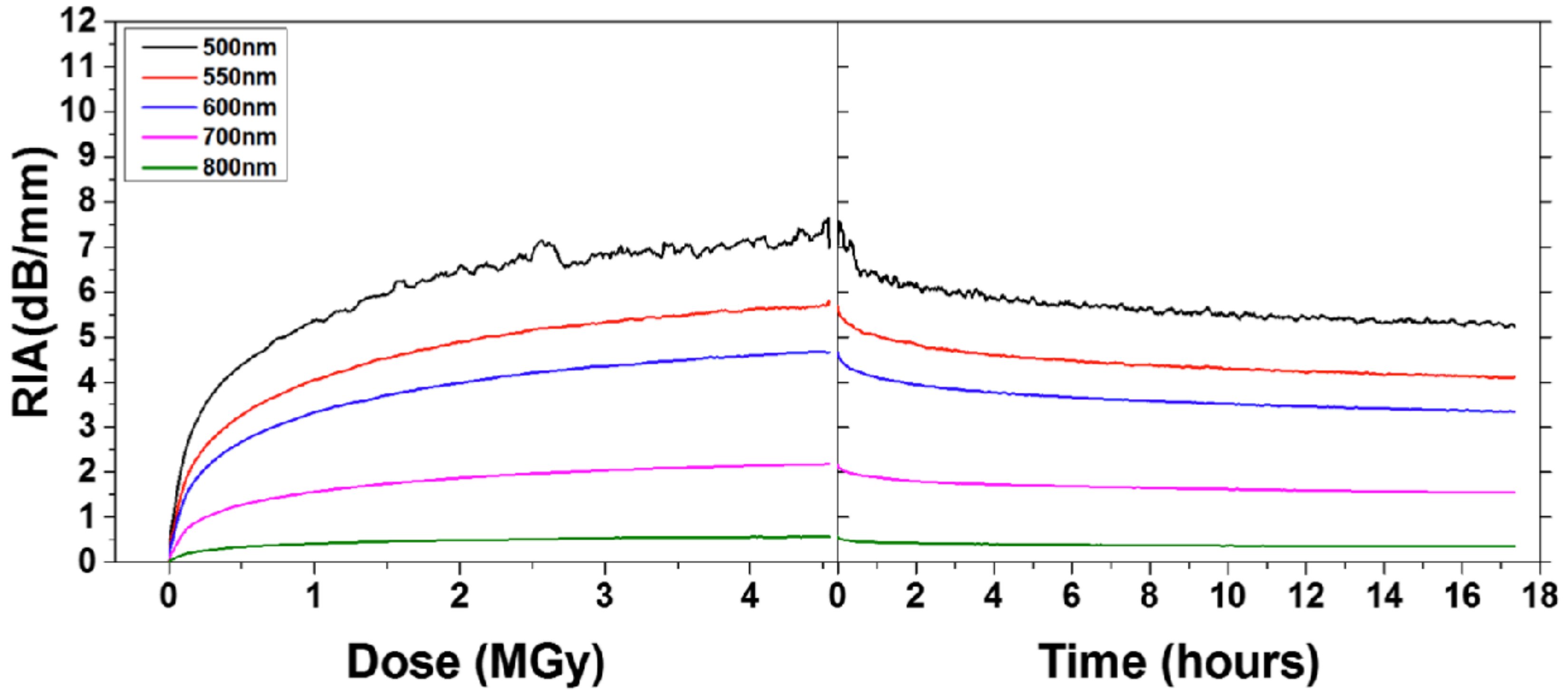
Time Dependence of Optical Attenuation

- Traditional measurements → underestimation of *in-situ* radiation-induced attenuation (RIA) effects due to lack of proper accounting for transient losses

Radiation-induced attenuation of BK7 glass



Girard et al., 2018 IEEE TRANSACTIONS ON NUCLEAR SCIENCE

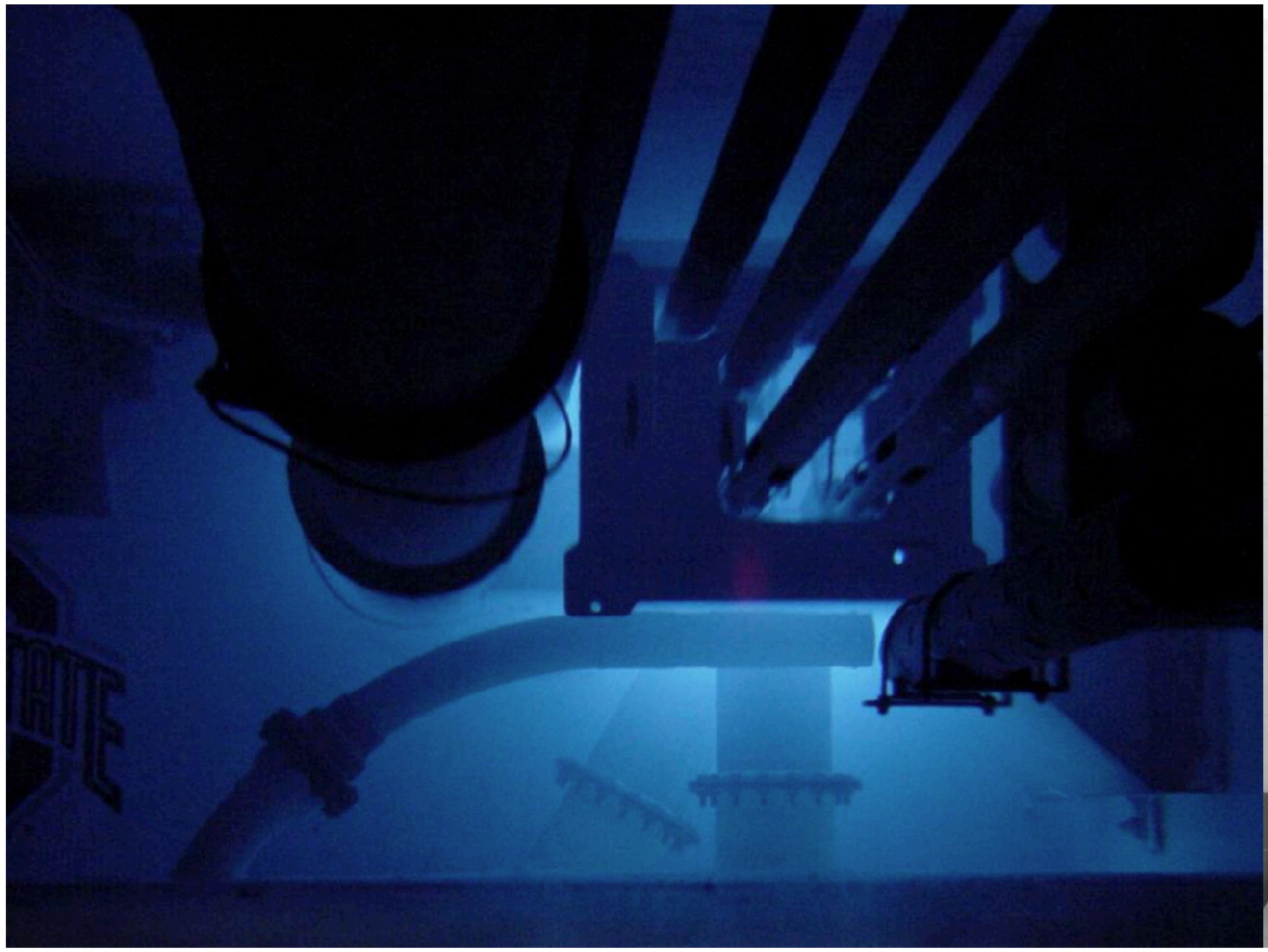


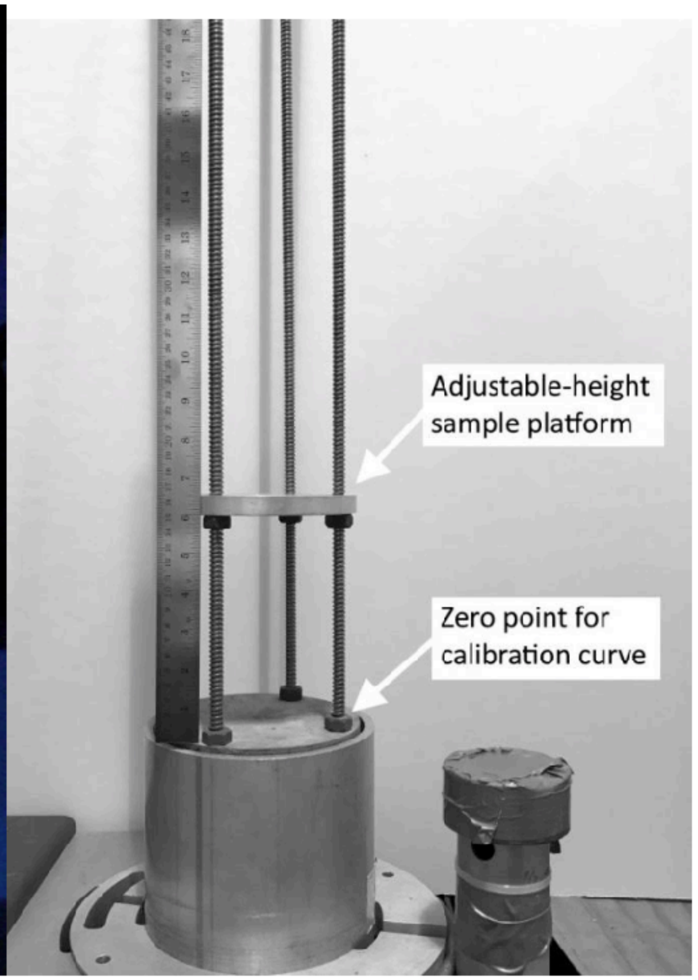
- Transient losses are only partially understood
- Depend on the optical material, dose, dose rate, temperature, as well as wavelength and injected optical intensity.

This Project Employs the OSU-NRL NSUF

- Open pool research reactor (500 kW)
- Multiple vertical dry tubes and beam ports
- Licensed to operate at thermal powers up to 500 kW
- Neutron flux ~$10^{12} – 10^{13}$ n/cm^2/s

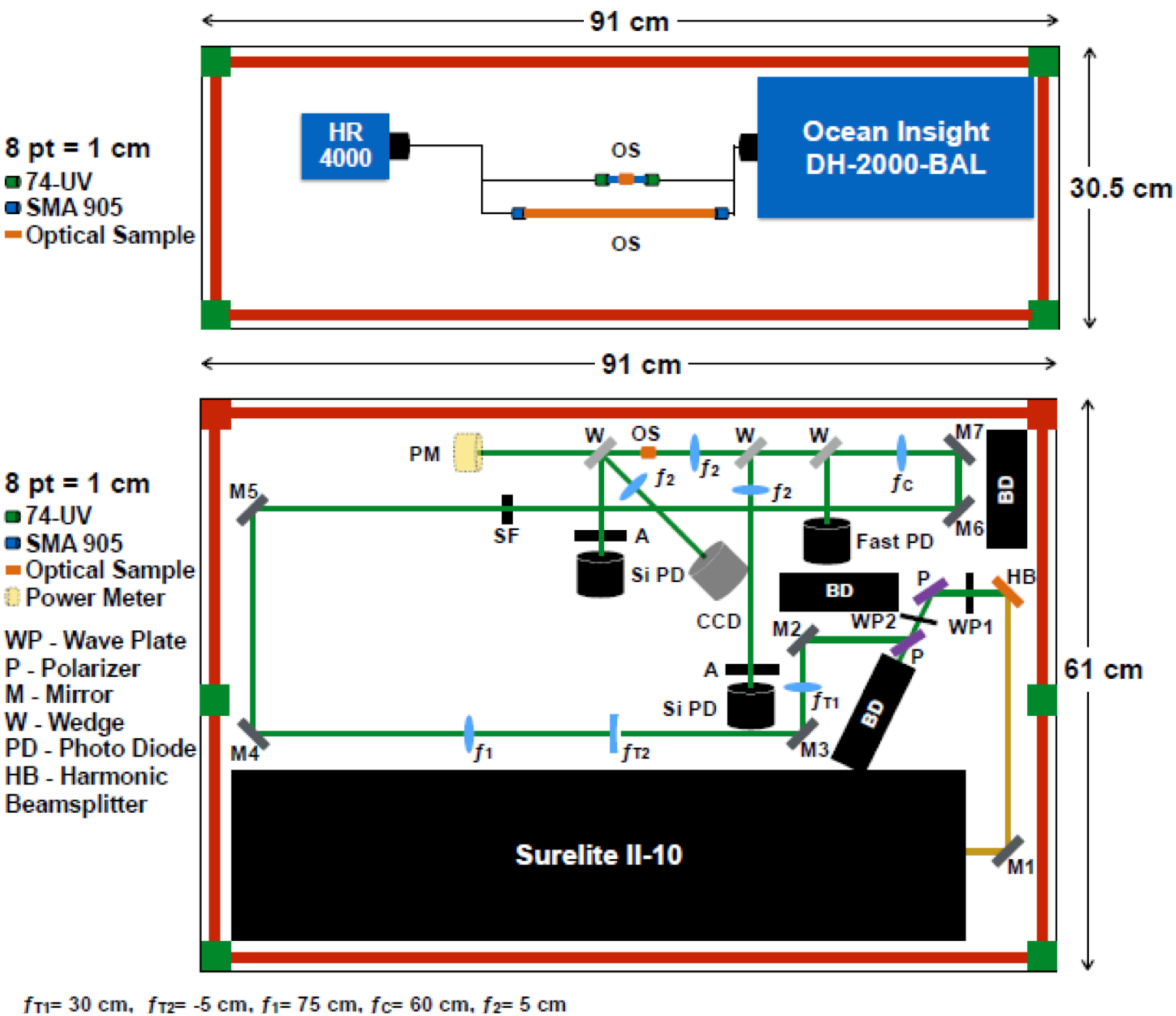
9.5” dry tube next to the reactor core





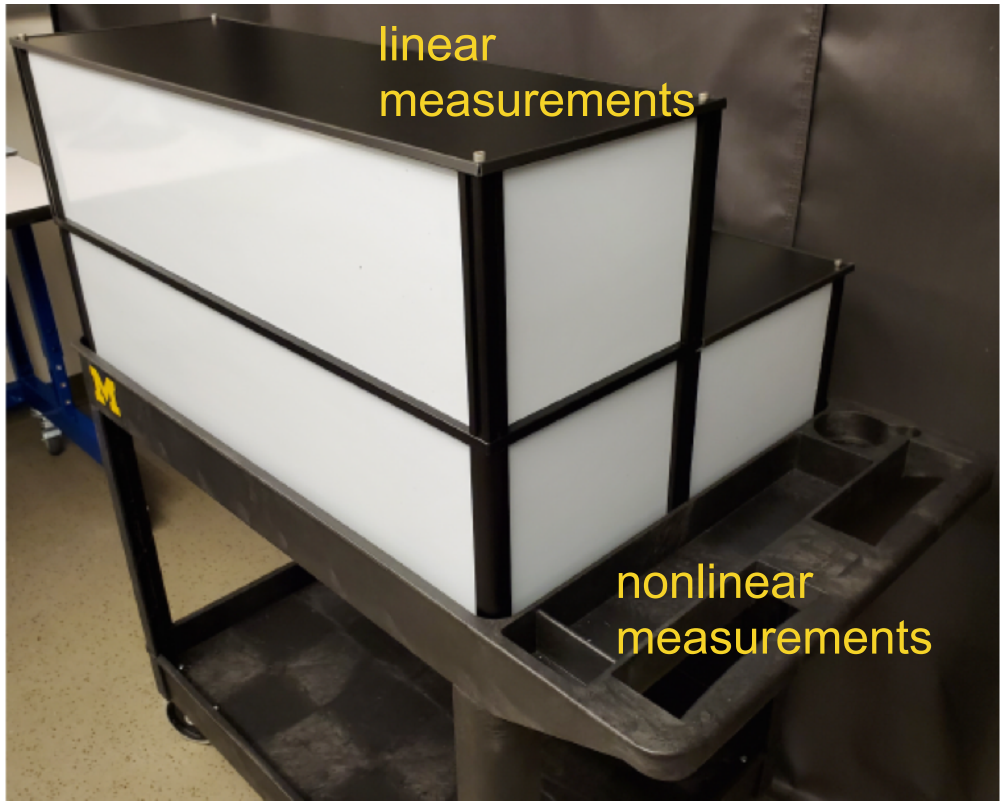
Sample plate and shielding for the gamma irradiator

We are Developing a Custom PIE Setup



- Irradiated samples will be characterized for their optical performance using a custom-designed and constructed mobile setup for Post-Irradiation Examination (PIE).
- PIE setup is under construction at UM and transported to OSU-NRL

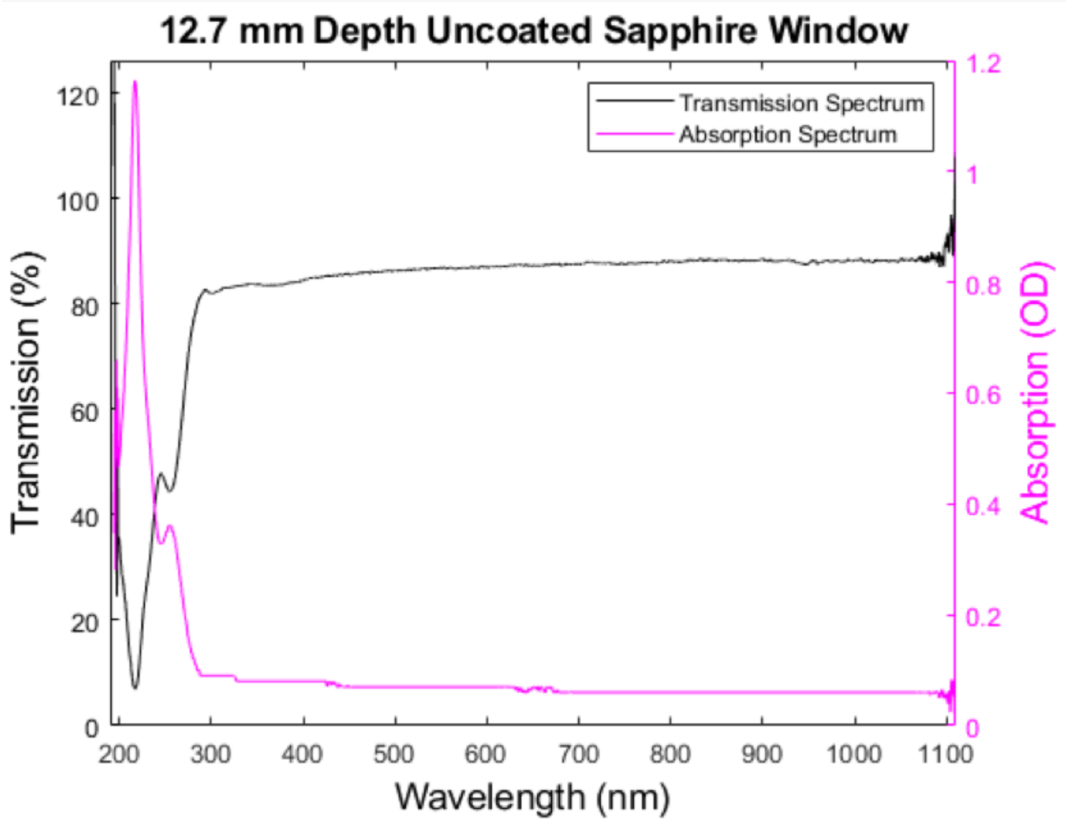
A Mobile PIE Setup is Under Construction and Test

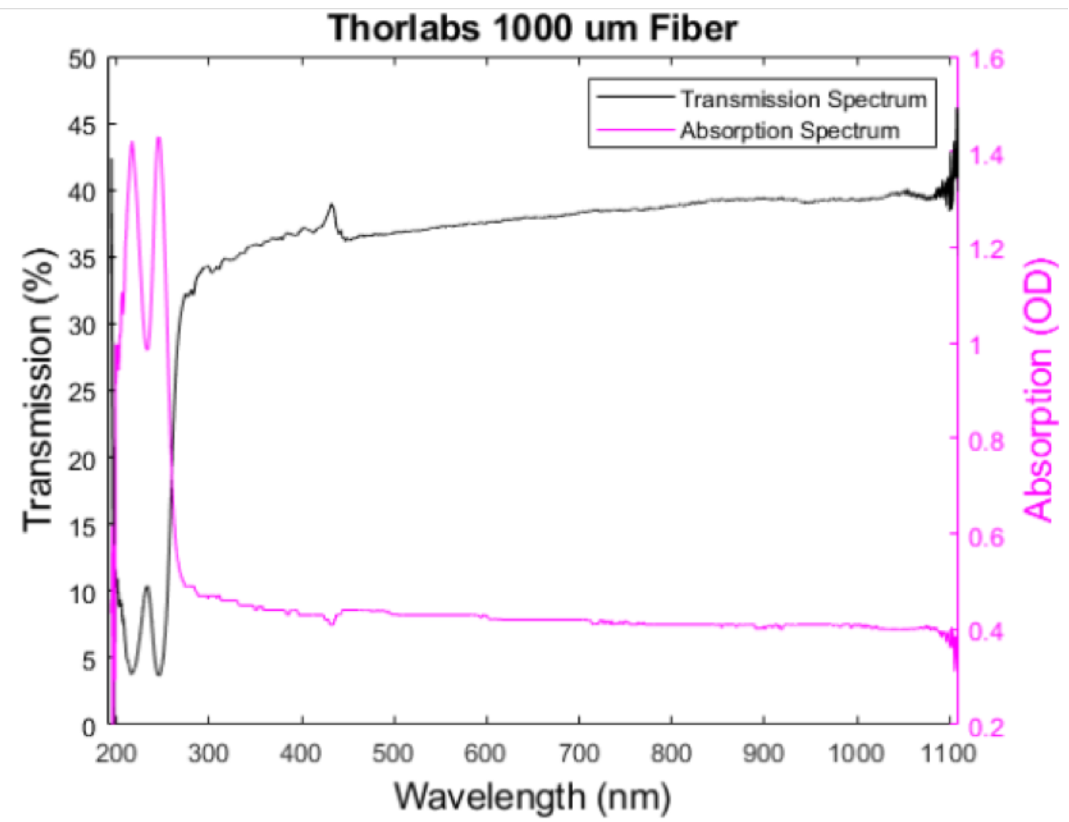


2-deck cart; 36” x 25" deck space

<u>Analysis Objectives</u>

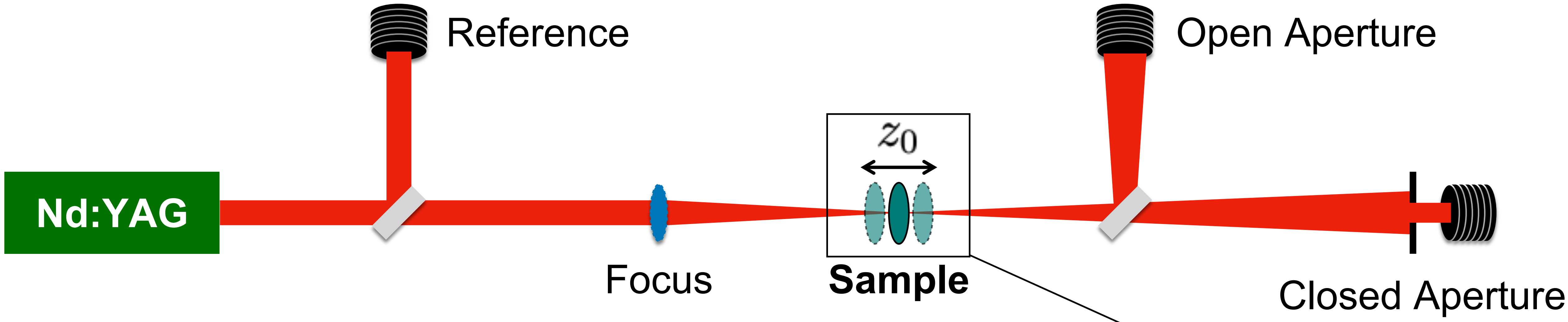
(1) Spectrophotometry
(2) Spectrally-resolved optical scattering
(3) Z-scan for nonlinear refractive index measurement

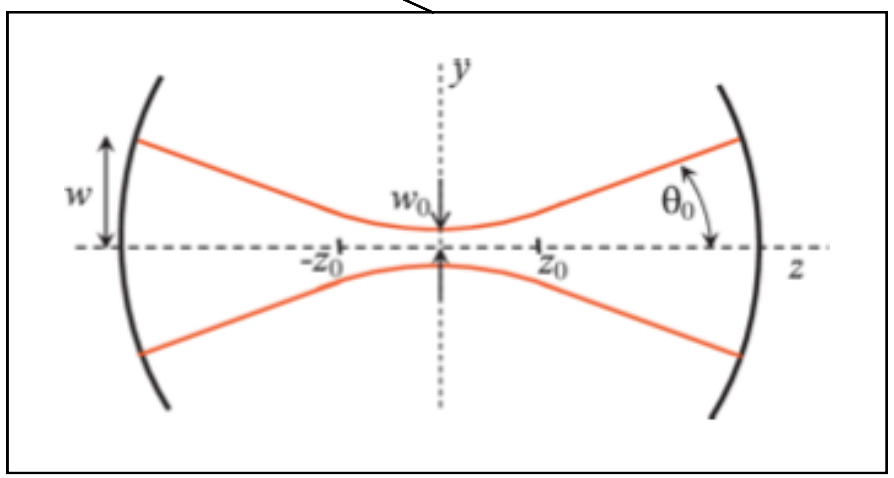




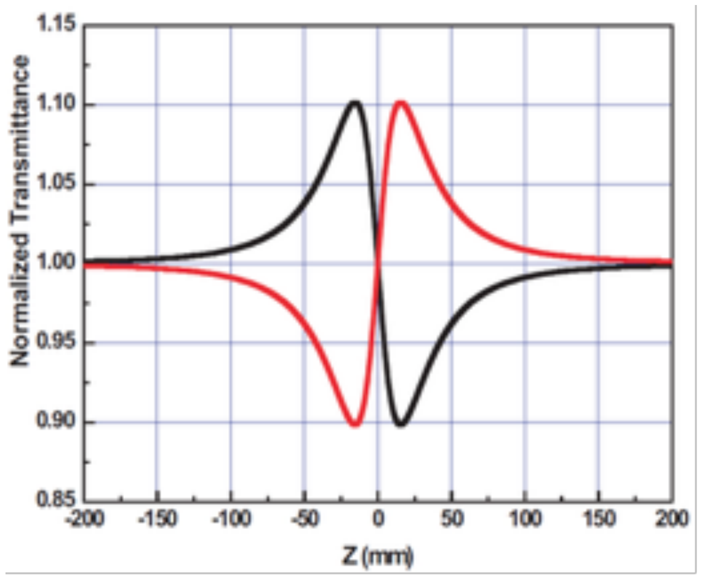
Linear absorption test

Measurement of Nonlinear Refractive Index: the Z-scan Technique

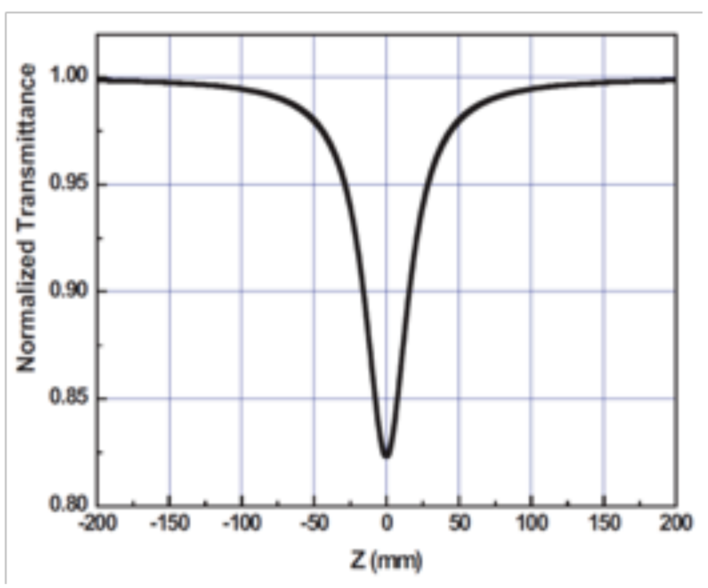




Closed Aperture: Nonlinear Refraction



Open Aperture: Nonlinear Absorption



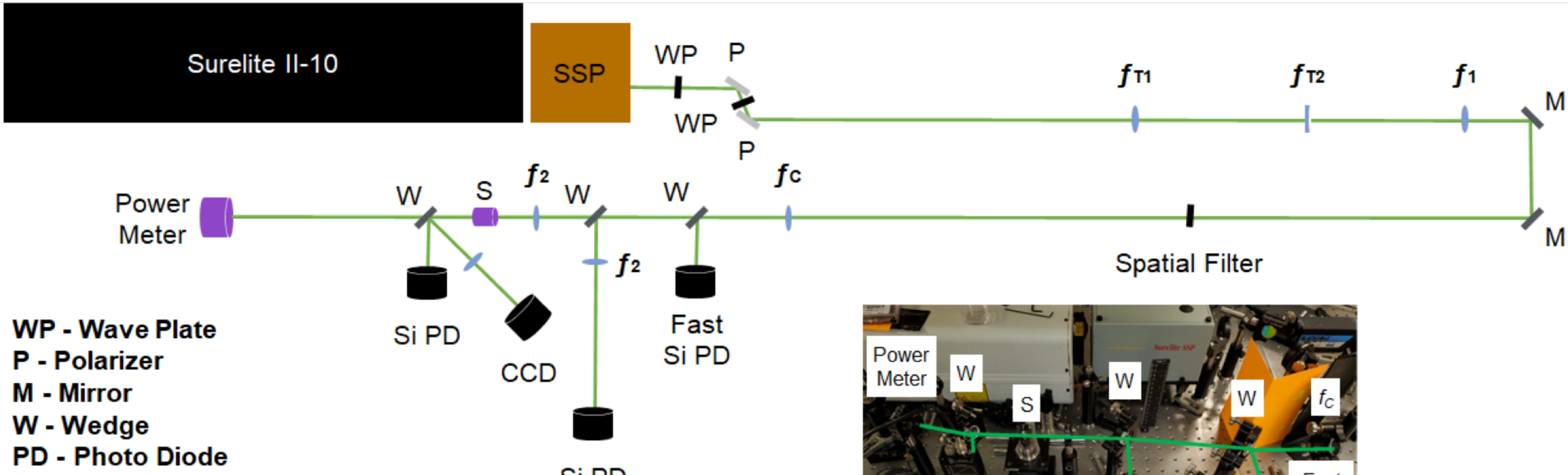
$\Delta\Phi_0$ = nonlinear phase shift

ΔT_{pv} = Δnormalized transmittance

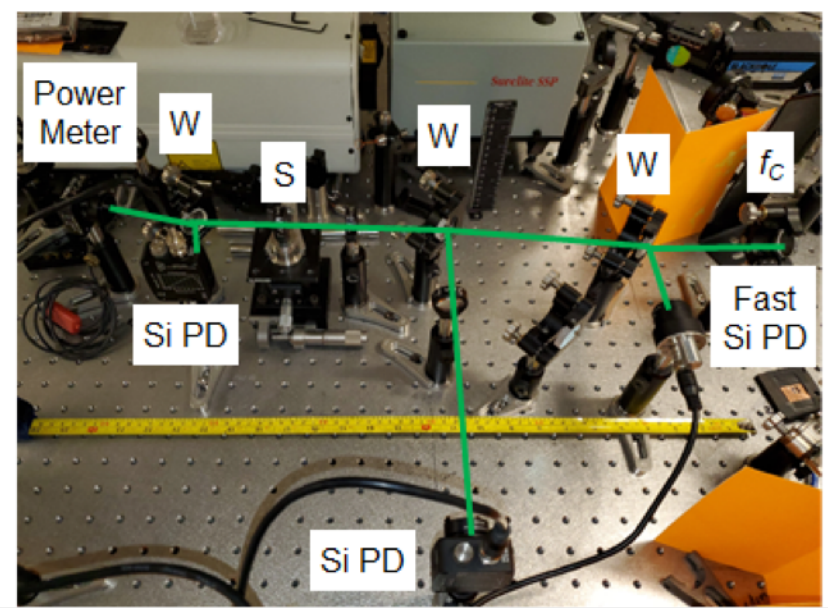
$$L_{eff} = \frac{1 - e^{-\alpha l}}{\alpha}$$

β = two-photon absorption coefficient

We are Experimentally Evaluating the Requirements for Z-scan

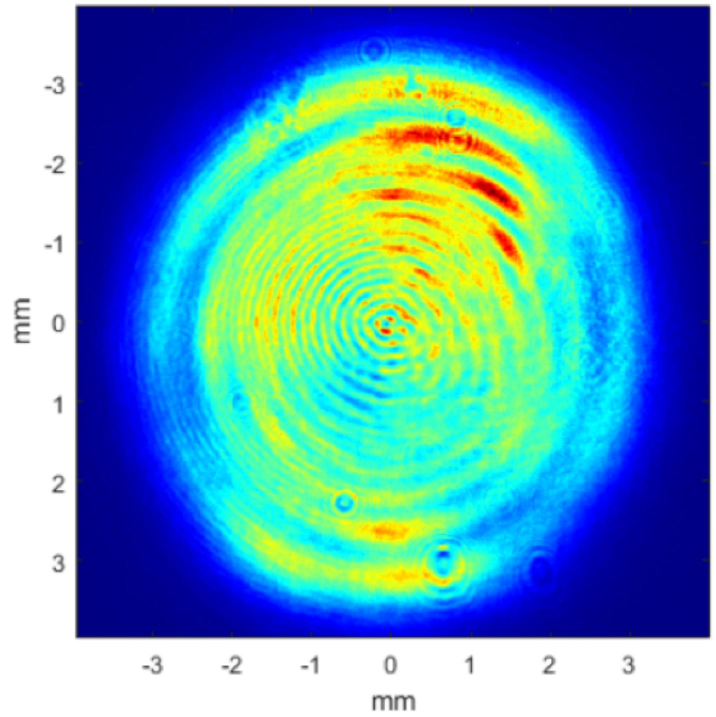


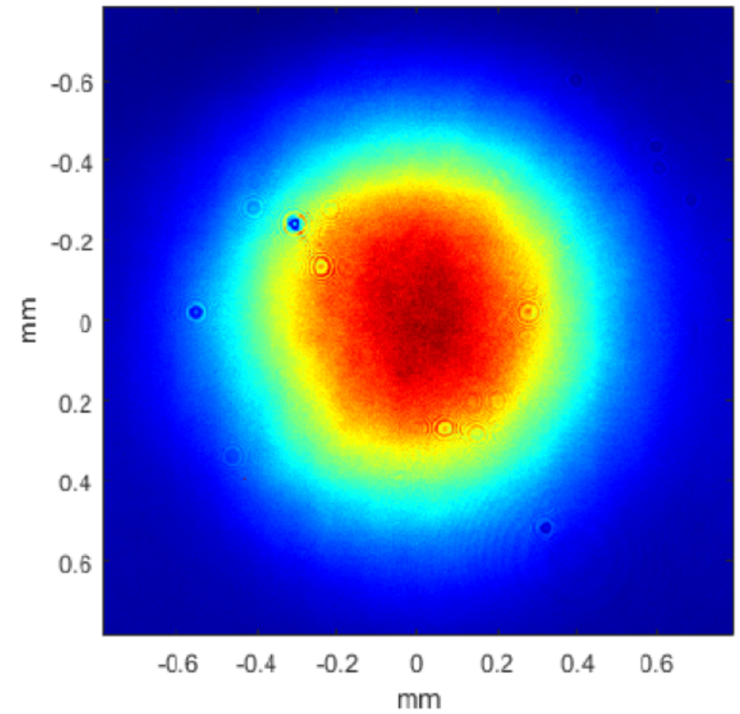
f_{T1} = 30 cm, f_{T2} = -5 cm, f_1 = 75 cm, f_c = 60 cm, f_2 = 5 cm



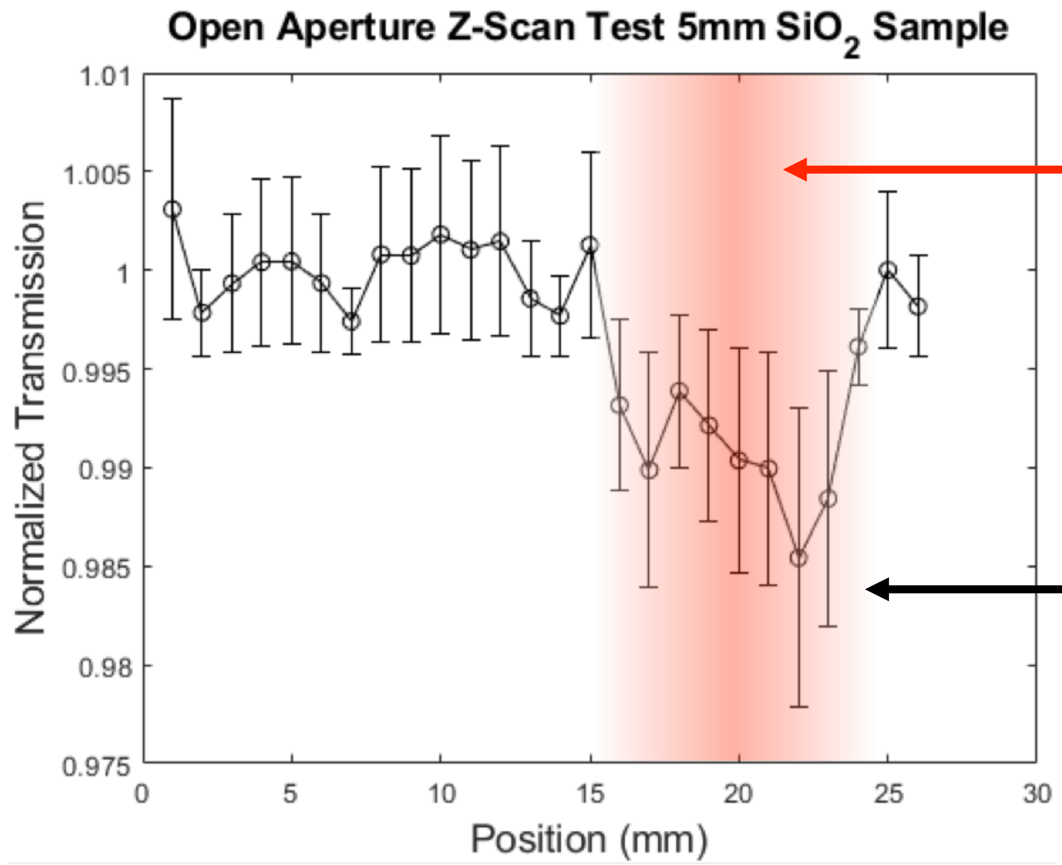
Z-scan Testing

before spatial filtering





after spatial filtering

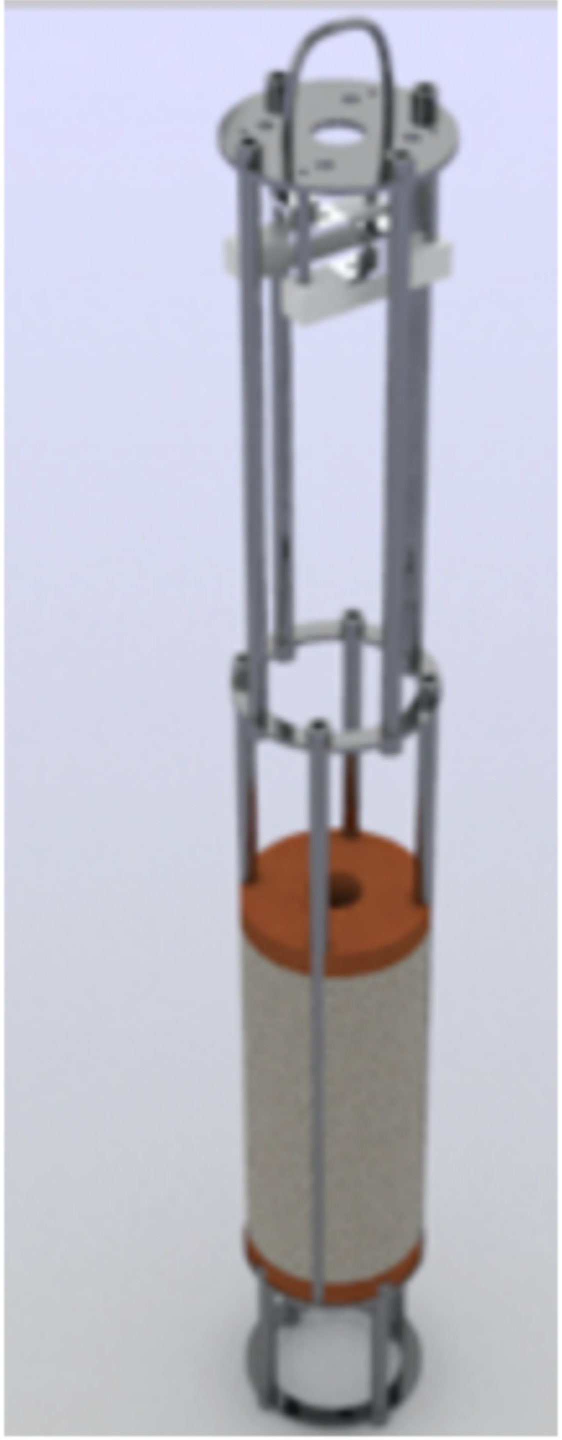


beam Rayleigh range

nonlinear absorption

Plan for Annealing Experiments

- Design and construct two compact furnaces suitable for sample heating to 1000 ºC.
- First furnace: insertion into gamma and neutron irradiation locations at OSU-NRL
- Second furnace: benchtop for post-irradiation heating.
- Heat and irradiate the samples concurrently.
- Each irradiated sample tested for
  - linear spectrally-dependent absorption
  - nonlinear absorption



Concept for a rig containing a furnace on the bottom

Irradiation Strategy

- Six types of optical windows and four types of fibers: fused silica, quartz, BK7G18, and sapphire
- Initial sample gamma irradiation at OSU; PIE at UM
- All other irradiations and PIE conducted at OSU.

Test	Dose	Thermal Annealing
Initial Gamma Irradiation	500 krad	No
Gamma Irradiation with Post Heating	500 krad 1 Mrad 3 Mrad	150 C Fiber 800 C Window
Neutron Irradiation with Post Heating	2×10^{16} n/cm^2 1×10^{17} n/cm^2 2.1×10^{17} n/cm^2	150 C Fiber 800 C Window
Gamma Irradiation with Concurrent Heating	500 krad 1 Mrad 3 Mrad	150 C Fiber 800 C Window
Neutron Irradiation with Concurrent Heating	2×10^{16} n/cm^2 1×10^{17} n/cm^2 2.1×10^{17} n/cm^2	150 C Fiber 800 C Window

Collaborations

Idaho National Laboratory

1. Integration of new instrumentation designs with reactor concepts such as GCFRs and LMCFRs
2. Advising of graduate students and postdocs

VTR VERSATILE TEST REACTOR

MicroNuclear LLC

1. Design window of conditions and specifications required for application of the new technology to a molten salt reactor environment
2. Develop a workable design concept that facilitates the integration of the new technology into a maturing reactor design

KAIST

1. Robust and radiation-resilient in-situ laser spectroscopic sensing techniques and devices that will apply to monitoring of coolant and fuel- coolant environments in advanced nuclear reactor systems
2. Hybrid sensing method for molten salt environments

Conclusion

- The project seeks to address a cross-cutting research need for design and operation of advanced optical instrumentation
- We are developing an understanding of radiation damage in optical materials that comprise instrumentation suitable for application in new reactor concepts
- Accomplishments in FY 2020:
  - specification and procurement of test samples
  - mobile PIE system construction
  - development of supporting experimental component and protocols with the NSUF collaborators
  - initiation of INERI collaboration
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