Radiation-Induced Attenuation and Nonlinear Optical Properties of Fused Silica and Single-Crystal Sapphire

Chris Petrie

Milos Burger

4/17/2024

Contributions from T. Birri, T. Dixon, and K. Everett

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Radiation-Induced Attenuation and ~~Nonlinear Optical Properties~~ Post-Irradiation Annealing in Fused Silica and Single-Crystal Sapphire

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* Samples were determined to be too thin for nonlinear measurements after project award

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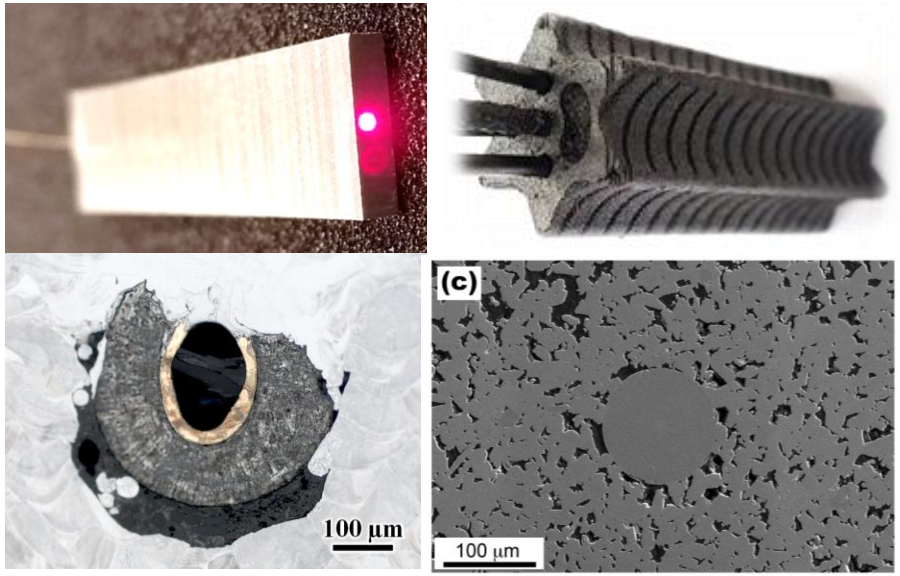
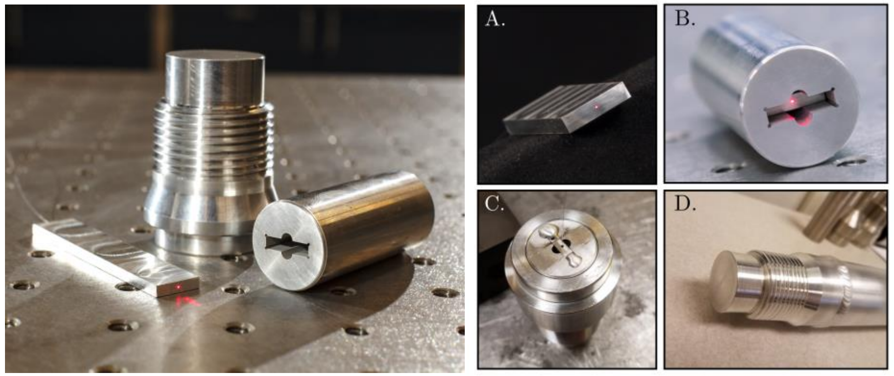
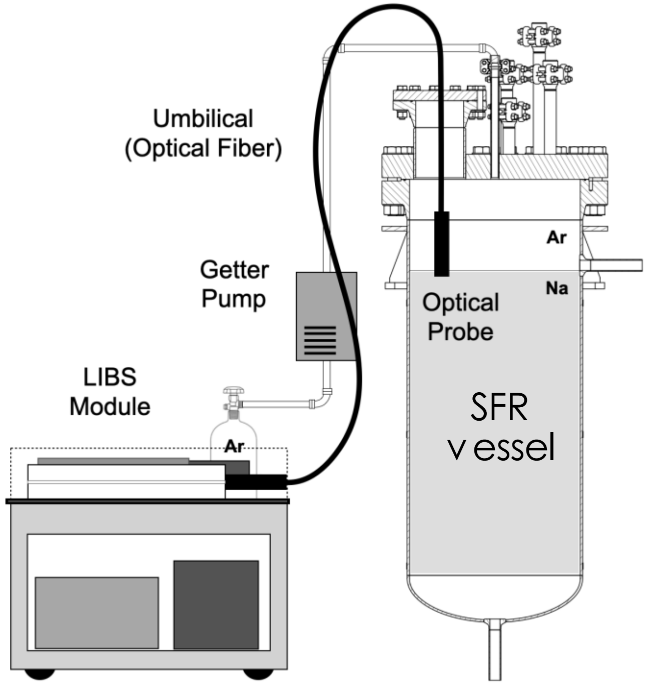
Nuclear applications for fiber optics (not a comprehensive list)



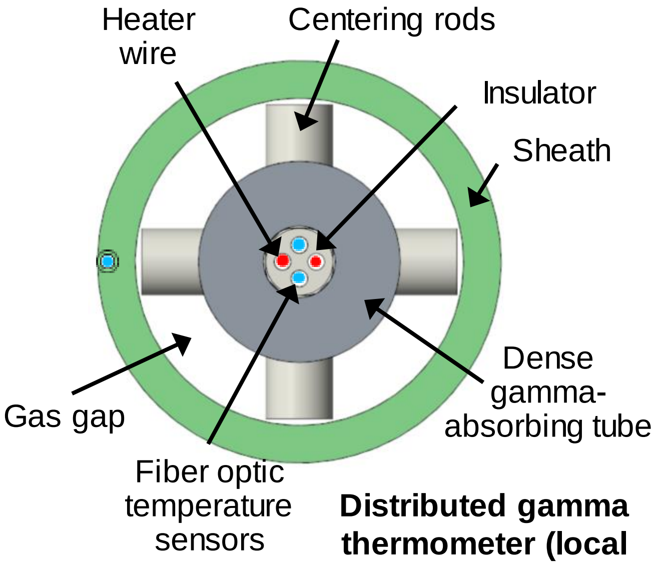
Sensors embedded in 3D printed stainless steel (left) or SiC (right) for local strain or vibration monitoring [1, 2]



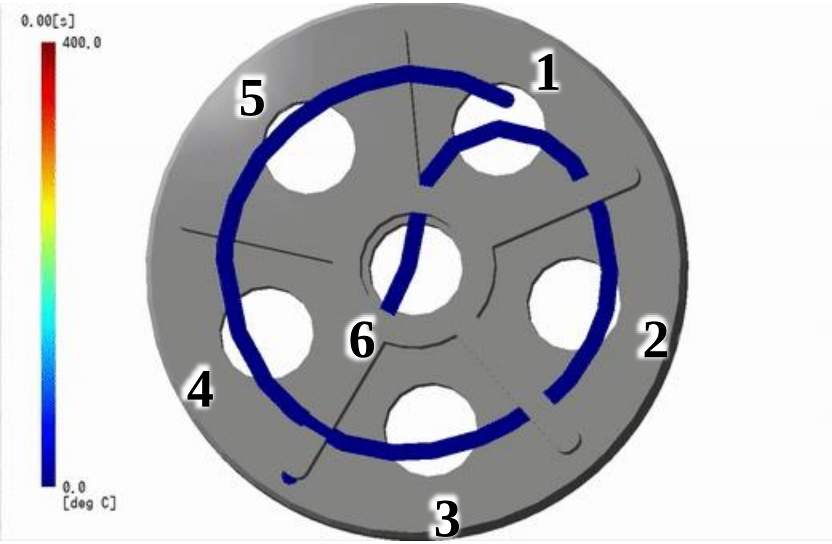
Embedded sensors for pressure, corrosion, or acoustic emissions [4, 5]



Trace O and H detection in SFRs, other impurities in MSRs



Distributed gamma thermometer (local power monitoring) [3]

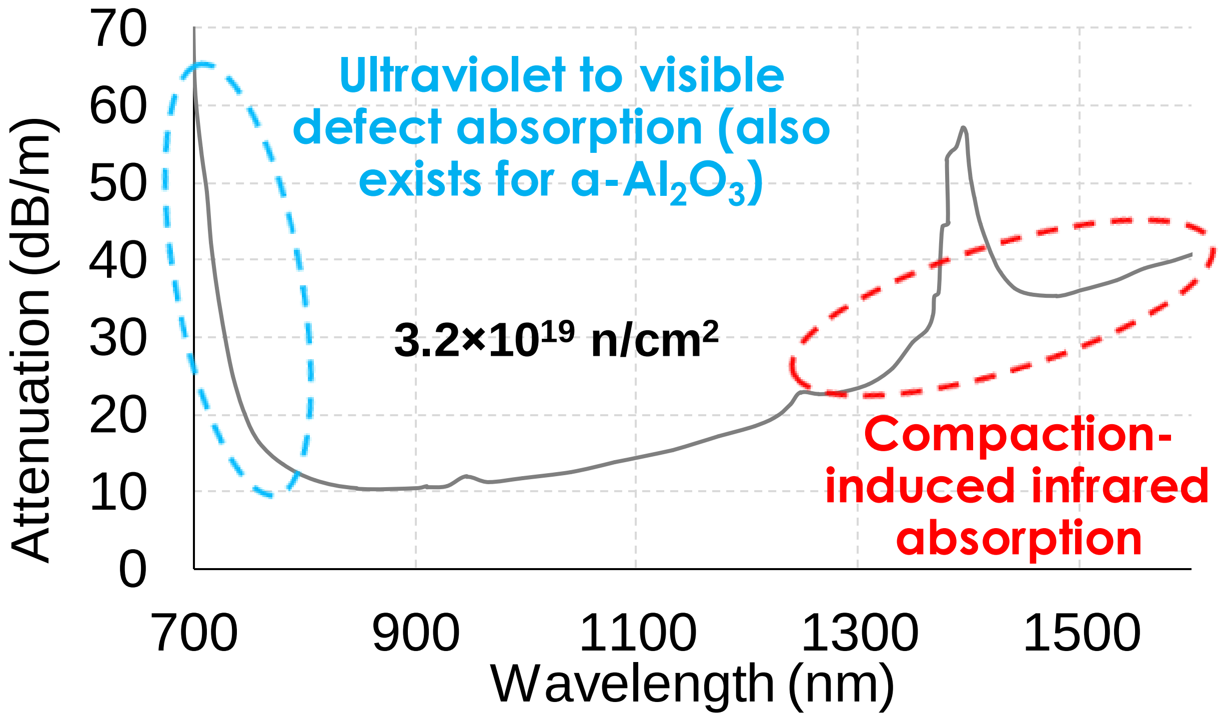


Local temperature measurements in an experiment simulating gas-cooled reactor core outlet mixing [6]

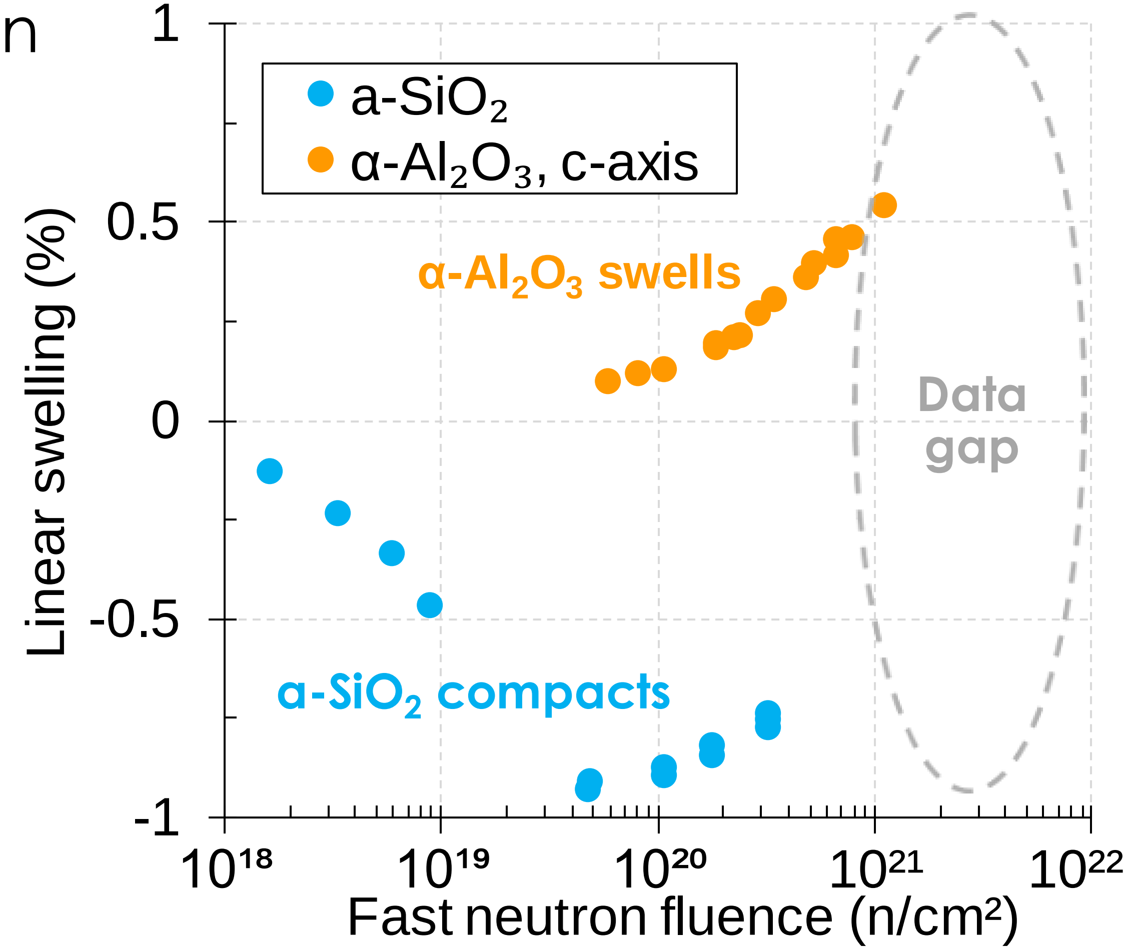
[1] H.C. Hyer et al., *Additive Manufacturing*, **52** (2022), 102681.
[2] C.M. Petrie et al., *Journal of Nuclear Materials* **552** (2021) 153012.
[3] A. Birri and T.E. Blue, *Progress in Nuclear Energy* **130** (2020) 103552.
[4] D.C. Sweeney, A.M. Schrell, and C.M. Petrie, *IEEE Trans. Instrum. Meas.* **70** (2021) 1-10.
[5] C.M. Petrie, D.C. Sweeney, and Y. Liu, US Non-Provisional Patent No. US 2021/0033479 A1, Application No. 16/865,475, published February 4, 2021.
[6] H.C. Hyer et al., "Toward Local Core Outlet Temperature Monitoring in Gas-Cooled Nuclear Reactors Using Distributed Fiber-Optic Temperature Sensors," *Applied Thermal Engineering* (under review).

Limitations for a-SiO_2 and α-Al_2O_3 fiber-based sensors

- Both sensors suffer from signal attenuation and drift under neutron irradiation
  - Need to quantify at higher dose and temperature



Low-temperature (<100°C) attenuation in a-SiO_2 [1]



Signal drift from low-temperature (~100°C), radiation-induced dimensional change [2,3]

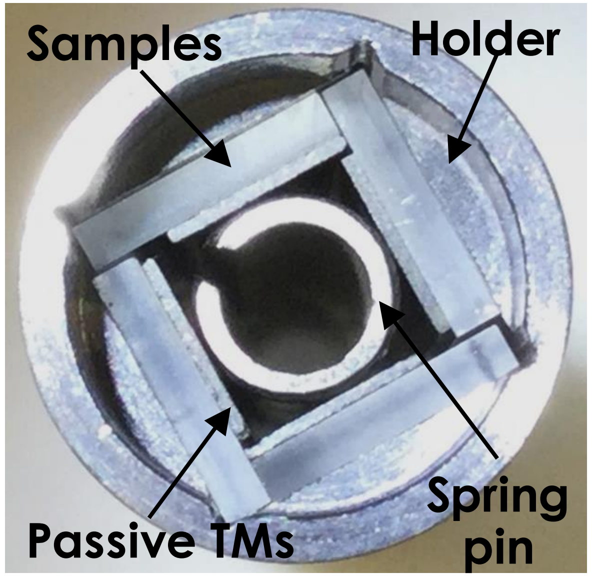
[1] G. Cheymol et al., "High Level Gamma and Neutron Irradiation of Silica Optical Fibers in CEA OSIRIS Nuclear Reactor," IEEE Trans. Nucl. Sci. **55** (2008) 2252-2258
[2] W. Primak, "Fast-Neutron-Induced Changes in Quartz and Vitreous Silica," Phys. Rev. **110** (1958) 1240-1254.
[3] R.S. Wilks et al., "The irradiation-induced macroscopic growth of α-Al_2O_3 single crystals," J. Nucl. Mat. **24** (1967) 80-86.

Inexpensive, passive HFIR irradiation tests

- "Slab" specimens irradiated in the High Flux Isotope Reactor (HFIR)
  - 4 low-OH a-SiO_2, 4 high-OH SiO_2, and 4 α-Al_2O_3 per capsule
  - 16 mm long × 5 mm wide × 0.85 mm thick
  - Design temperatures of 100, 300, and 600°C confirmed by passive SiC temperature monitors (TMs)

Irradiation test matrix

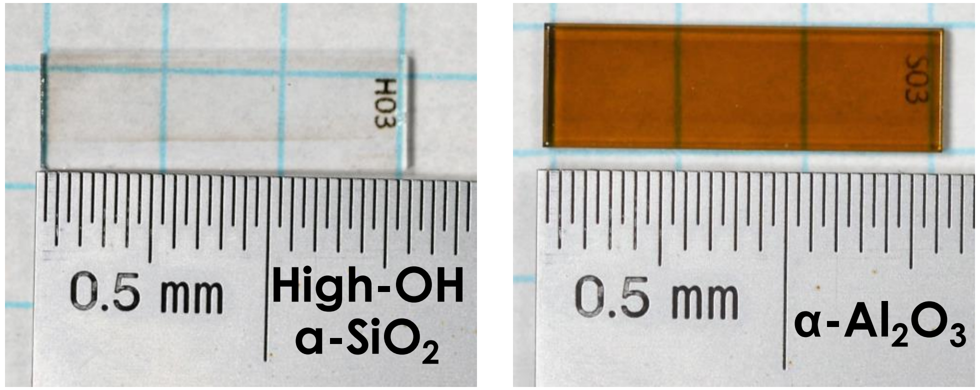
Fast neutron fluence (n/cm^2)	Measured specimen temperatures (°C)		
	Target 100°C	Target 300°C	Target 600°C
2.4×10^{21}	95	298	688
9.6×10^{21}	88	N/A	592



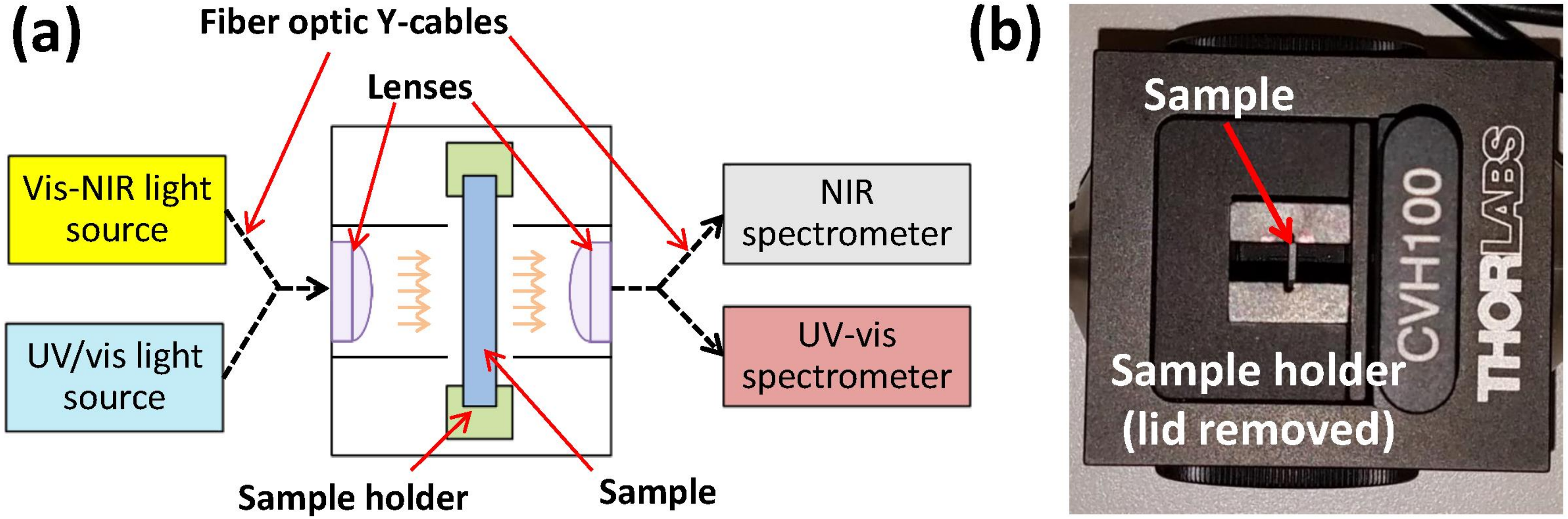
Capsule parts before (top) and after (bottom) assembly

Post-irradiation examination

- Optical transmission measured through specimen thickness
- Dimensional changes measured using micrometer
- Dilatometry to measure recovery of radiation-induced dimensional changes



Post-irradiation specimen pictures



Vis = visible; NIR = near-infrared region; UV = ultraviolet

Schematic (a) and picture (b) of optical measurement system

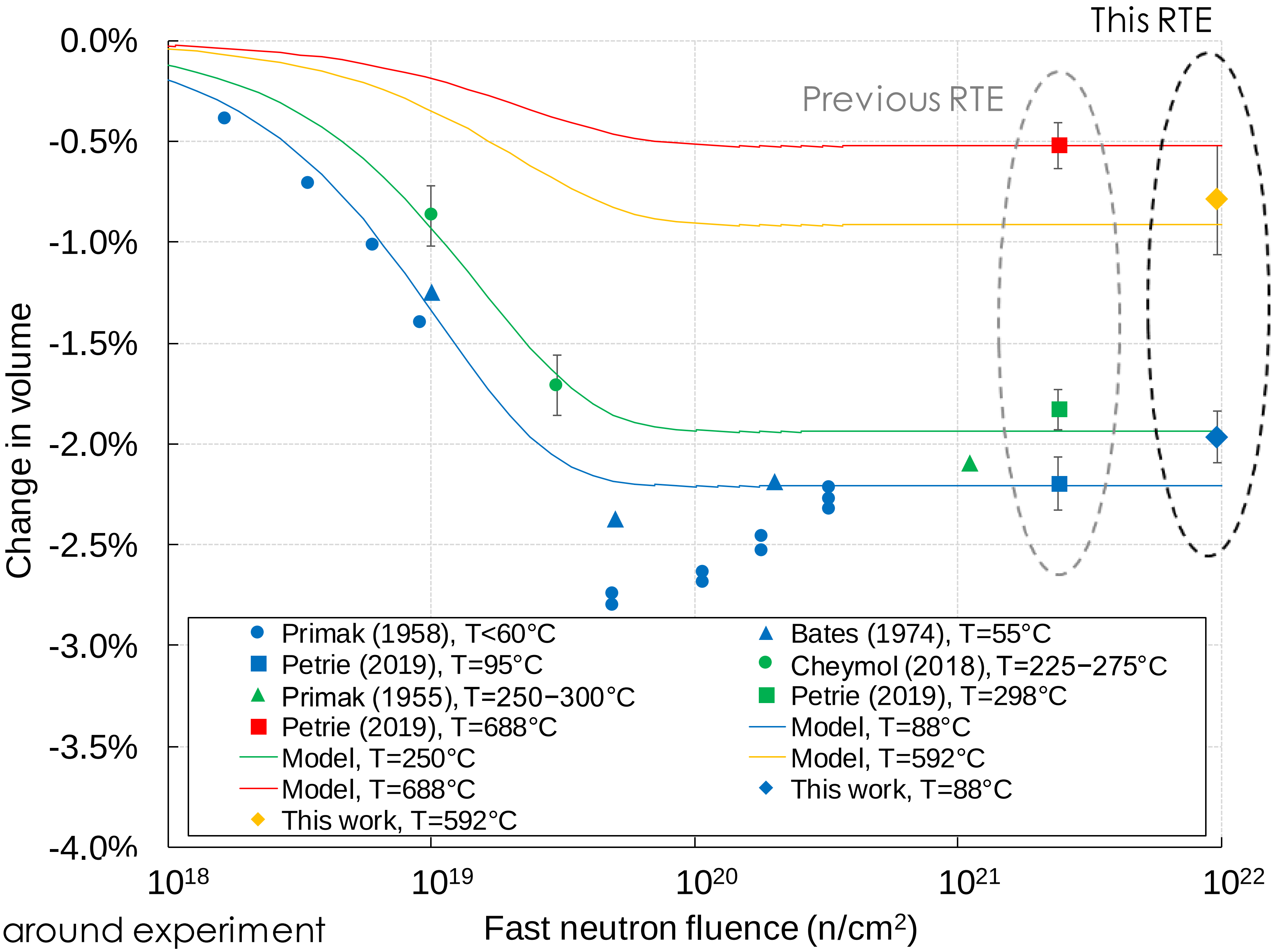
Optical measurements

Reprinted from “High-dose temperature-dependent neutron irradiation effects on the optical transmission and dimensional stability of amorphous fused silica,” *Journal of Non-Crystalline Solids* Vol 525 (2019), C.M. Petrie, A. Birri, and T.E. Blue, with permission from Elsevier.

a-SiO_2 radiation-induced dimensional change

New data compared to previously developed model

- Good agreement at 592°C
- Further emphasizes missing physics at <100°C (swelling after peak compaction)



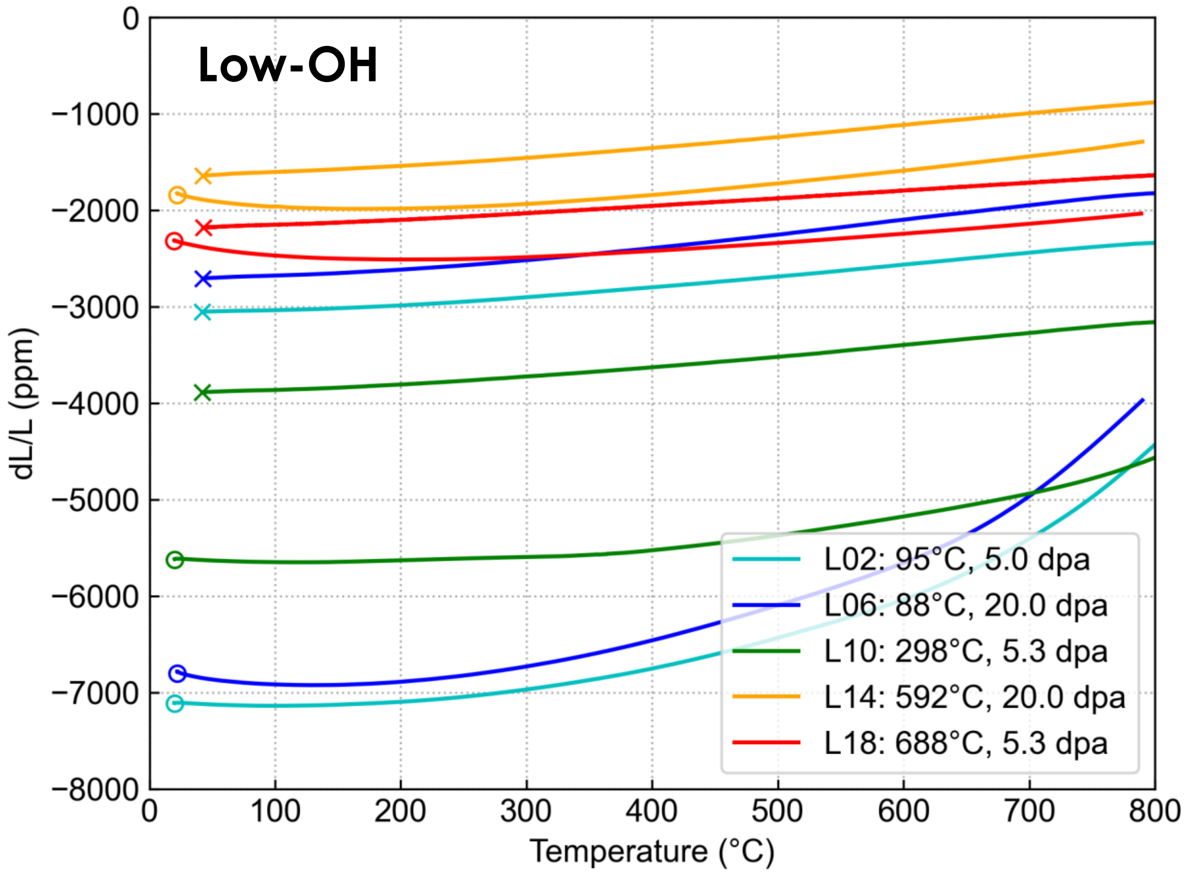
RTE = rapid turnaround experiment

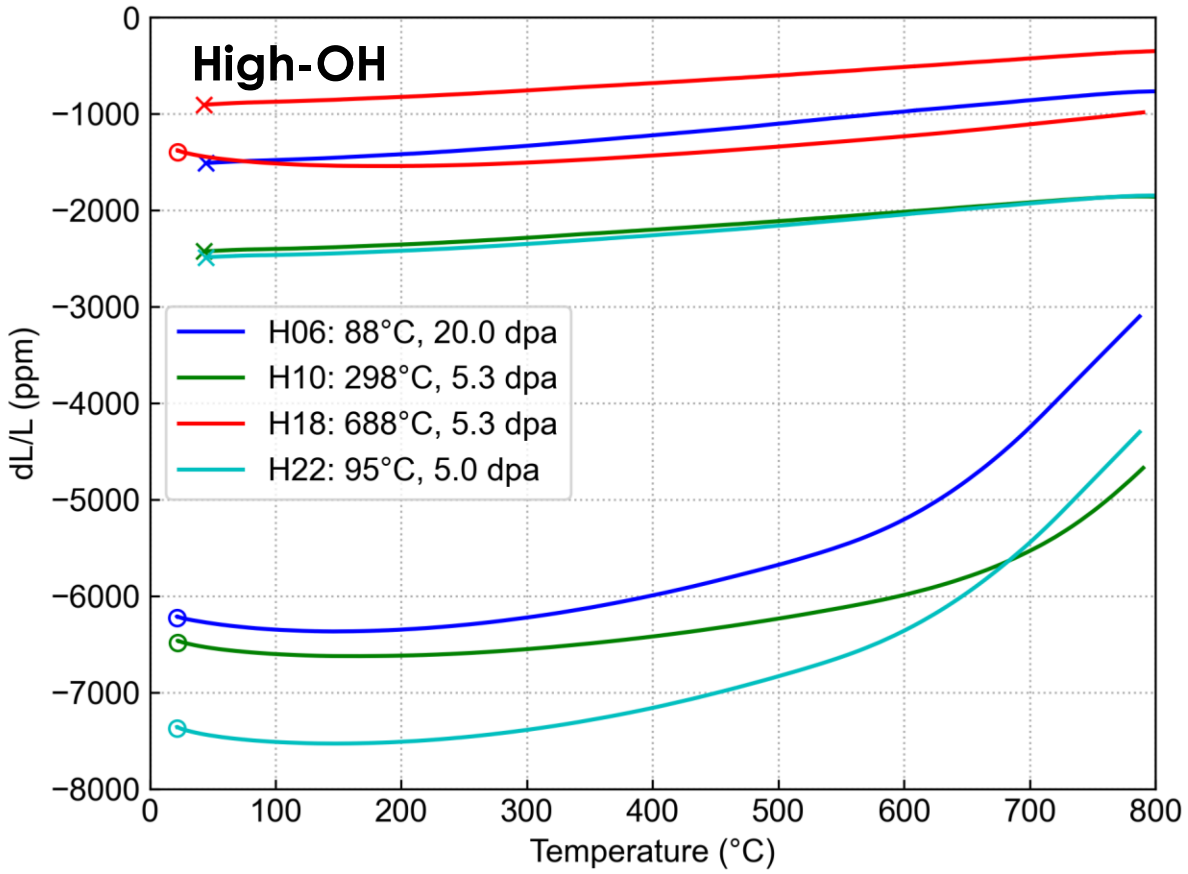
Post-irradiation annealing of a-SiO_2 radiation-induced compaction

- Initial recovery of swelling caused by low-temperature gamma irradiation after reactor shutdown?
- Significant recovery of radiation-induced compaction, particularly for samples irradiated at <300°C and heated to >500°C
  - More significant in high-OH samples

○ Start of heating, relative to pre-irradiation length

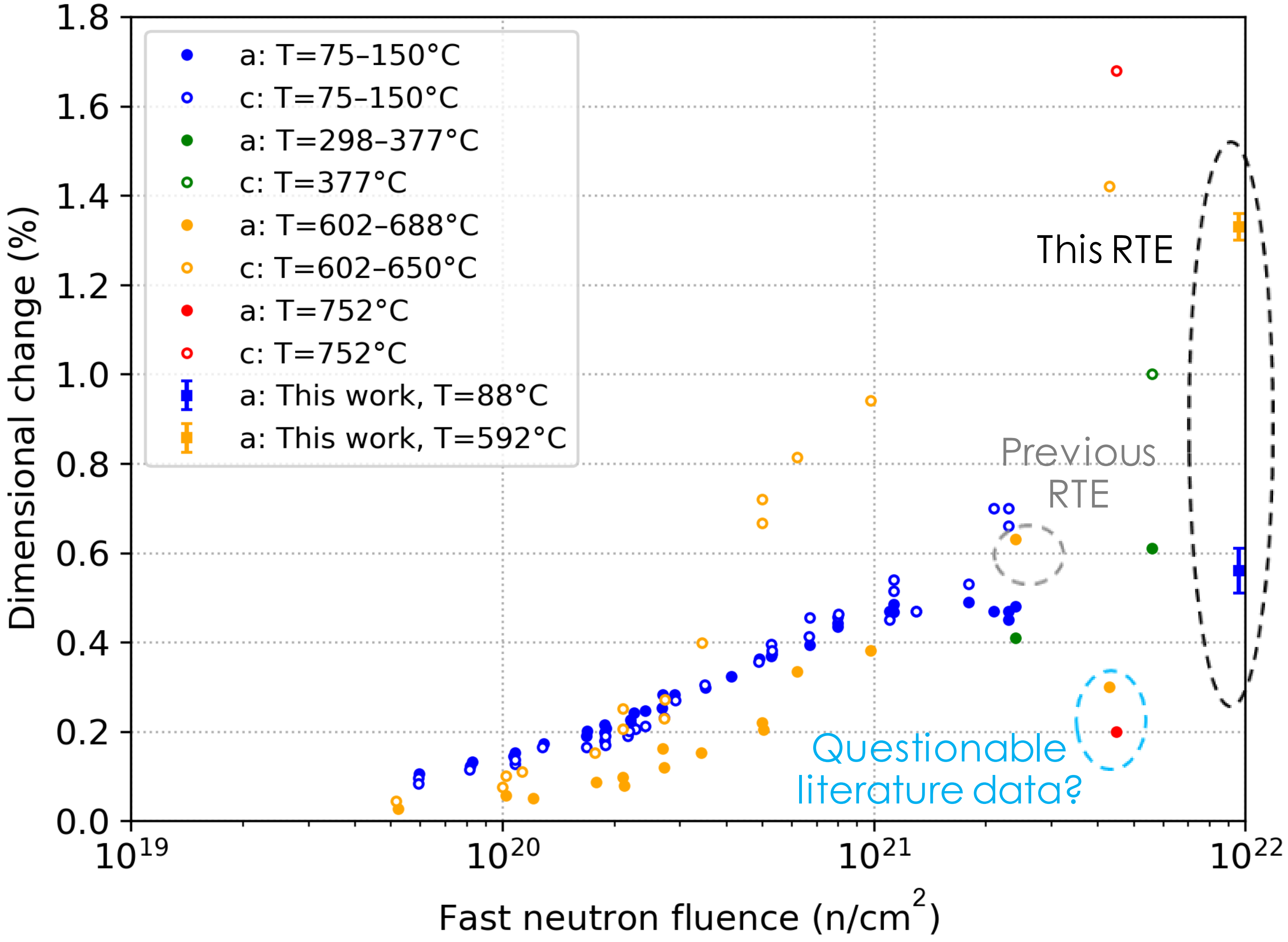
✕ End of heating , relative to pre-irradiation length





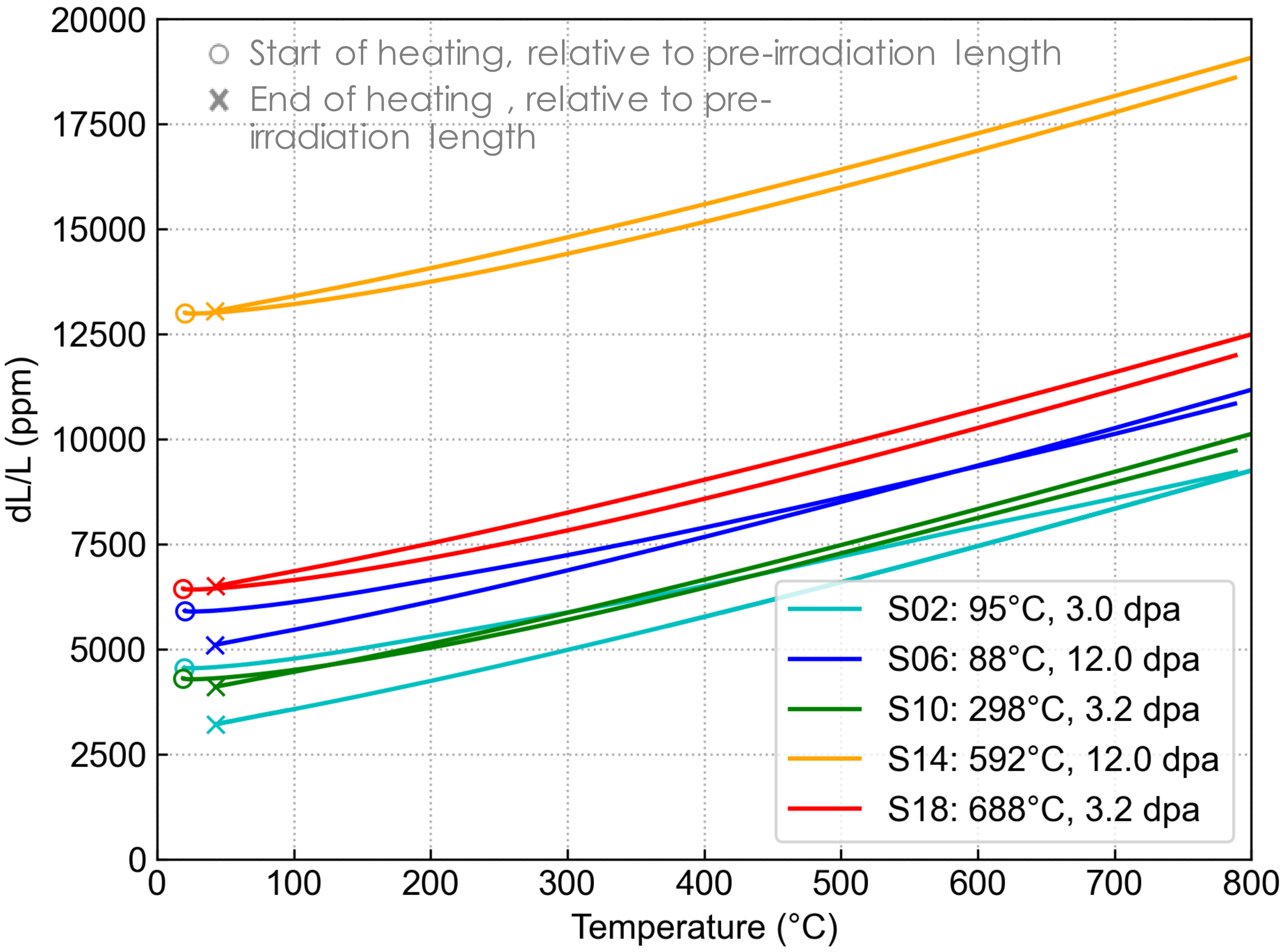
α-Al_2O_3 radiation-induced dimensional changes

- Unfortunately we couldn't accurately measure c-axis changes
  - Sapphire fibers are grown along c-axis
- Low temperature a-axis data consistent with literature
- High temperature a-axis data from this and previous RTE question validity of some literature data
  - Our data suggest anisotropic swelling is less than previously reported



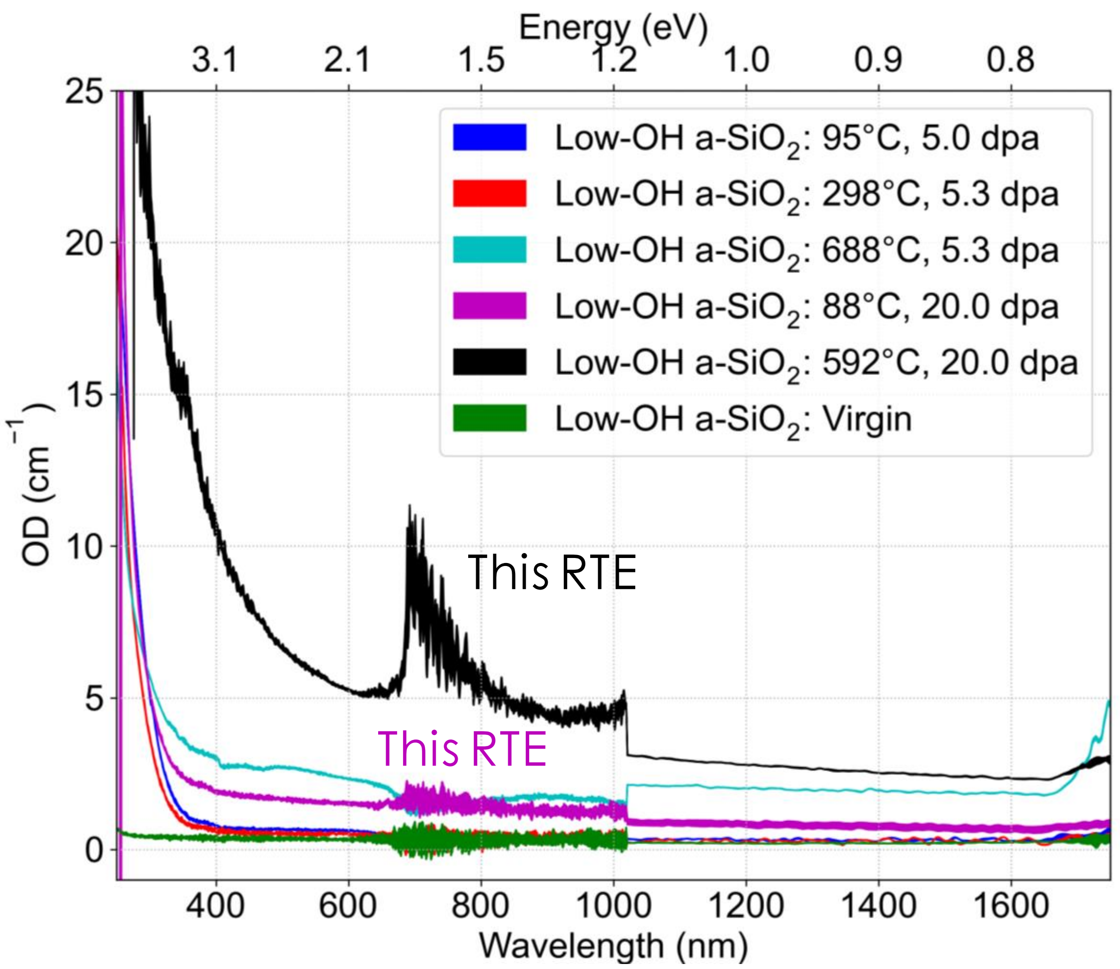
Post-irradiation annealing of α-Al_2O_3 radiation-induced swelling

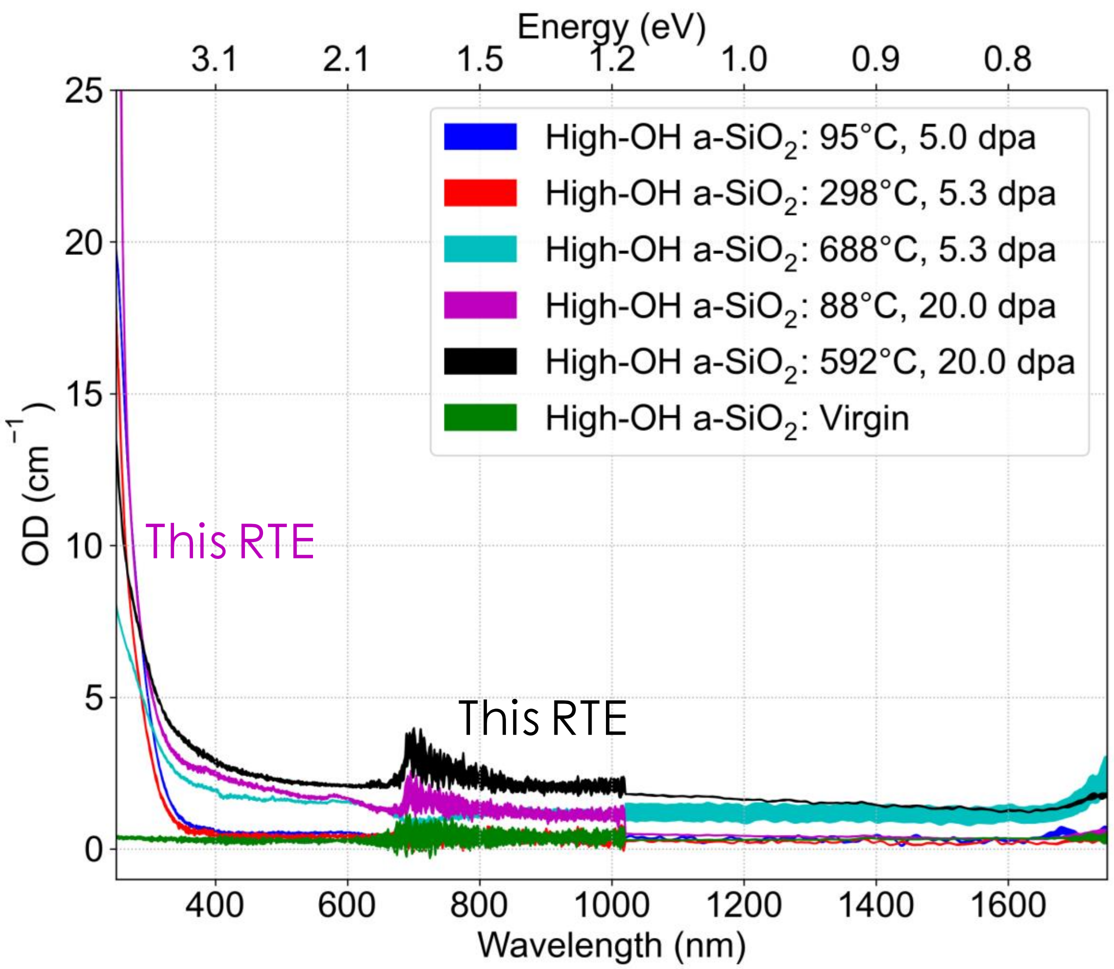
- Minimal recovery of radiation-induced swelling
  - Even in samples irradiated at <100°C and then heated to >800°C
  - Good in the sense that once the sensor drifts it wouldn't change much during temperature transients



$a\text{-}SiO_2$ transmission

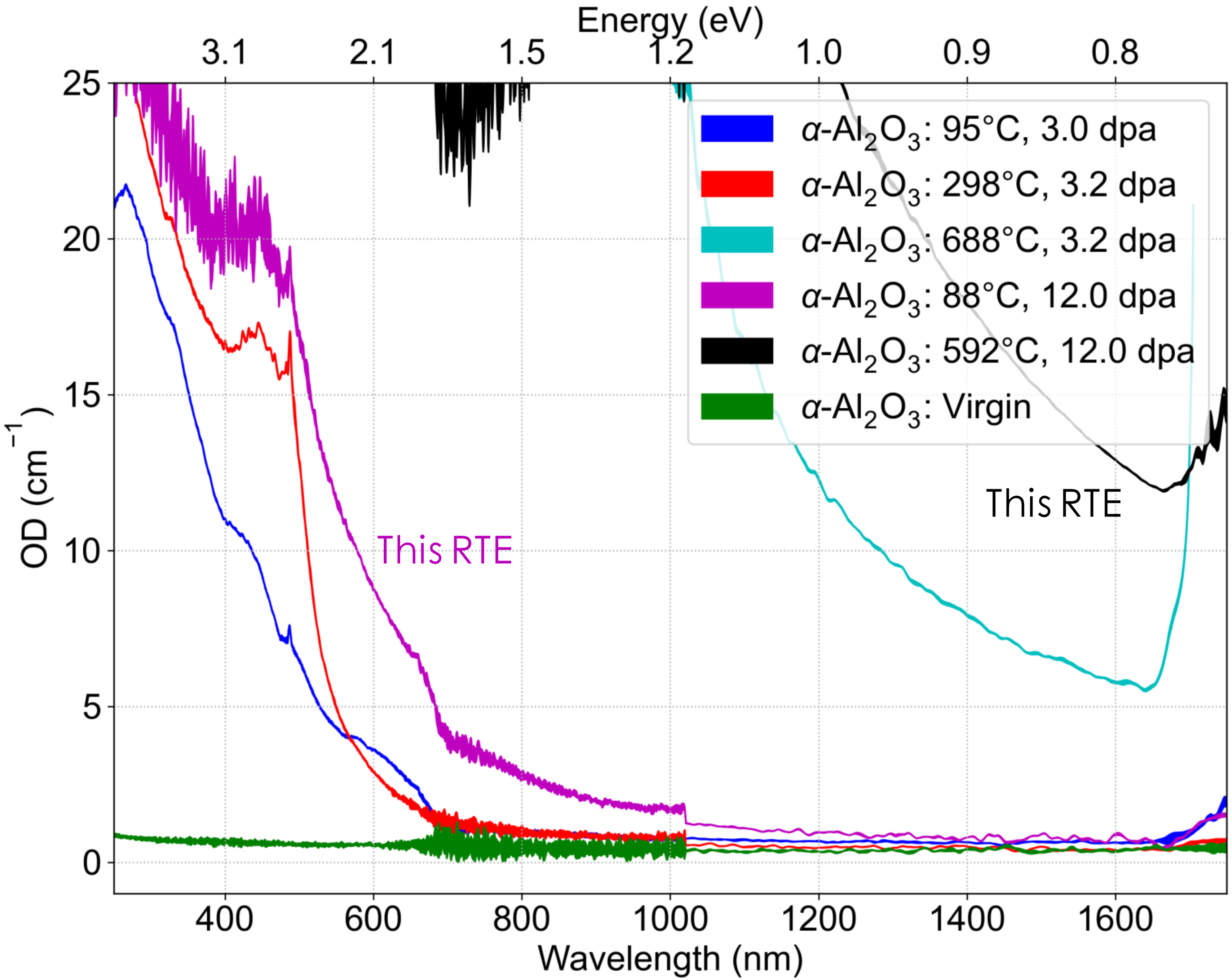
- Increases in attenuation at higher dose are minor, particularly in near-infrared (>1,000 nm) range
  - Broadband increases likely due to chemical interactions at higher temperatures, higher dose (time)
  - Origins of increases >1,600 nm are unclear (compaction effects should be lower at higher temperatures)





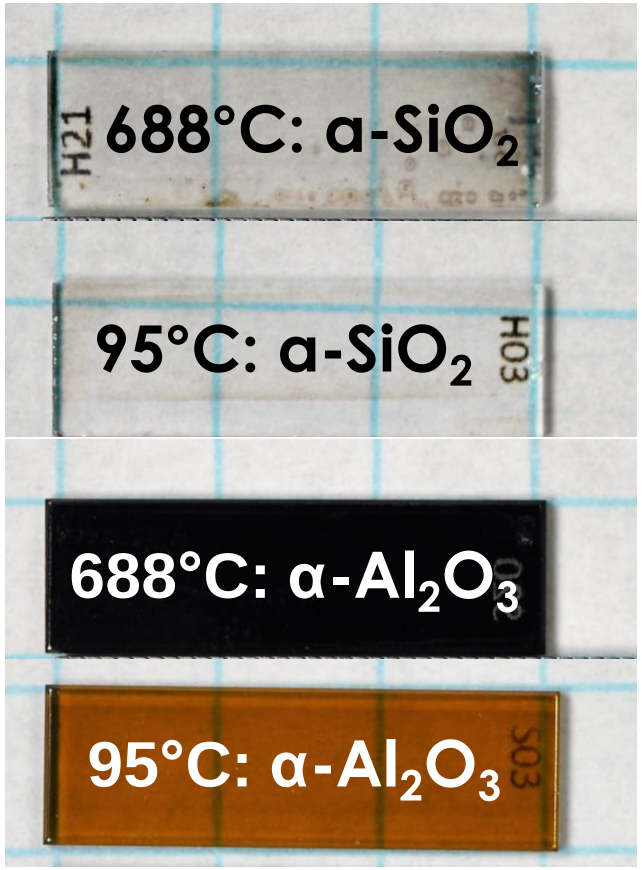
α-Al_2O_3 transmission

- Higher dose did not significantly affect attenuation after irradiation at ~90°C
- Prohibitive attenuation after 3.2 dpa at 688°C also observed after 12 dpa at 592°C
  - Advanced Sensors and Instrumentation (ASI) program supporting transmission electron microscopy: Could Rayleigh scattering from radiation-induced voids could provide an explanation?
  - Unclear what would cause the attenuation at > 1600 nm



Summary and conclusions

- Signal attenuation and drift are critical issues for both fused silica and single crystal sapphire optical fiber based sensors
  - Data is needed at higher temperatures and neutron fluence
- Examined bulk a-SiO_2 and α-Al_2O_3 samples irradiated in HFIR to 9.6×10^{21} n/cm^2 at ~100, and 600°C
- a-SiO_2 attenuation appears manageable but compaction-induced drift is significant and current models are not accurate at low temperatures and high dose
- α-Al_2O_3 attenuation is much higher than a-SiO_2, particularly at higher temperatures (~600–700°C)
  - ASI activity trying to identify potential mechanism



Post-irradiation pictures of a-SiO_2 and α-Al_2O_3 specimens

Questions?
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