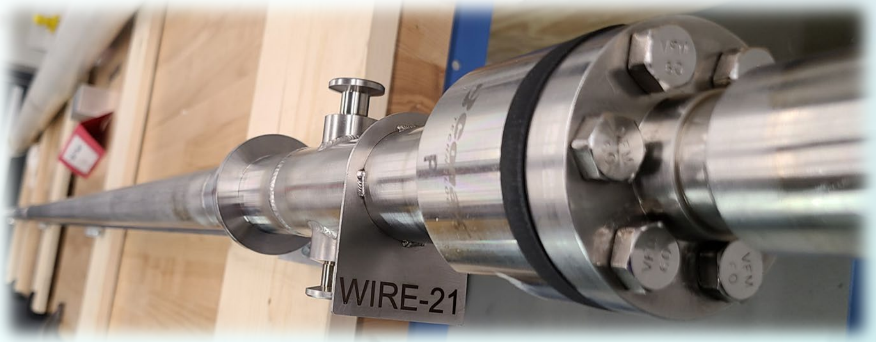
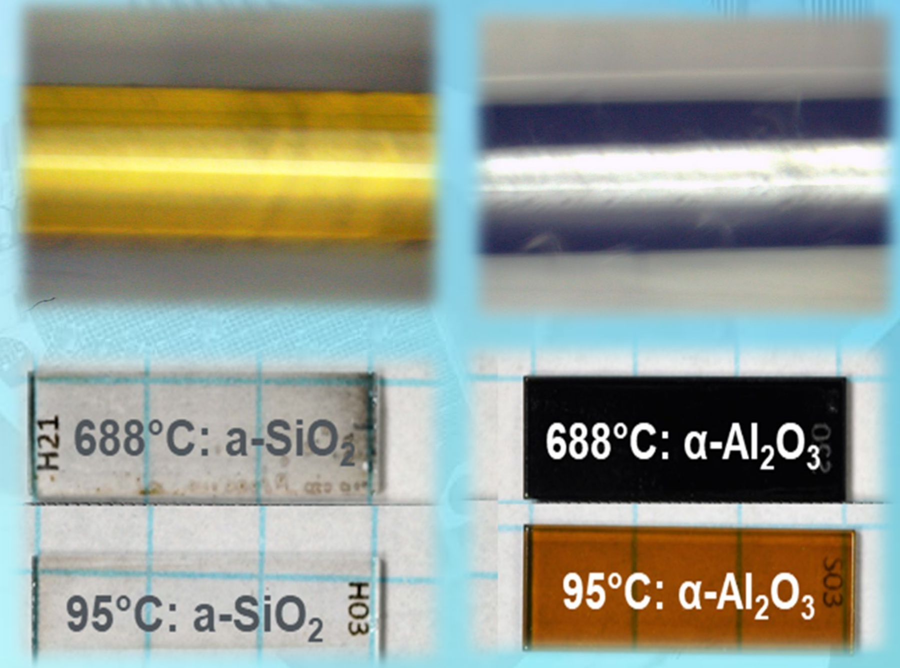
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

Optical Fiber - ORNL





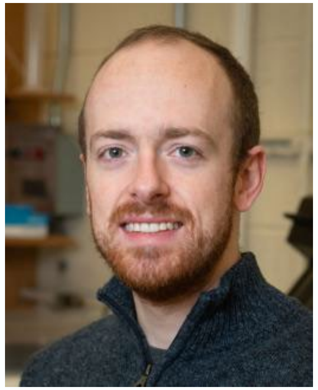
Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 4, 6-7, 2024

Chris Petrie, Group Leader, PI

Oak Ridge National Laboratory

Many thanks to the people that made this work happen!



Bryan Conry

Yan-Ru Lin

Matt Kurley

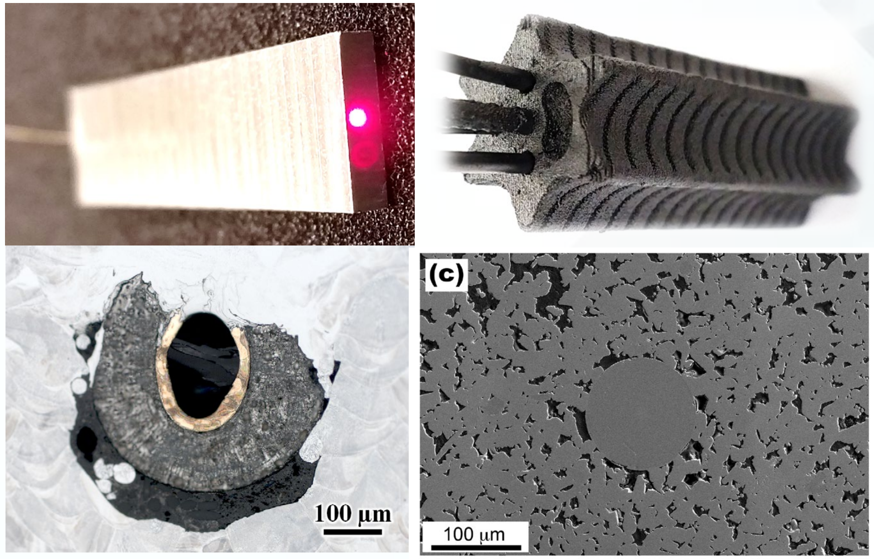
Chad Parish

Sabrina Calzada

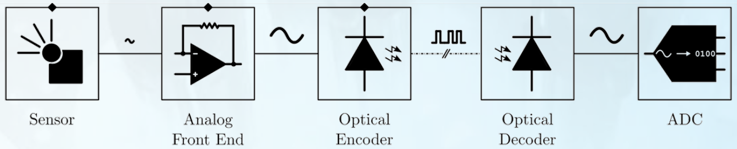
Eddie Lopez Honorato

Dan Sweeney

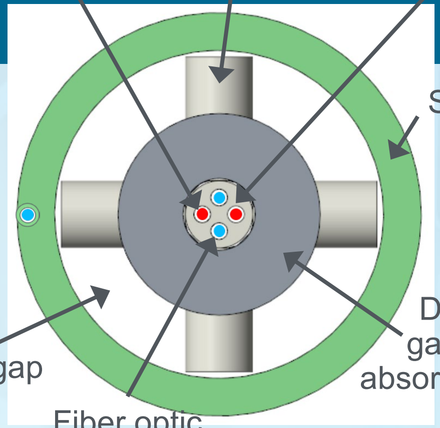
Potential nuclear applications of optical fibers



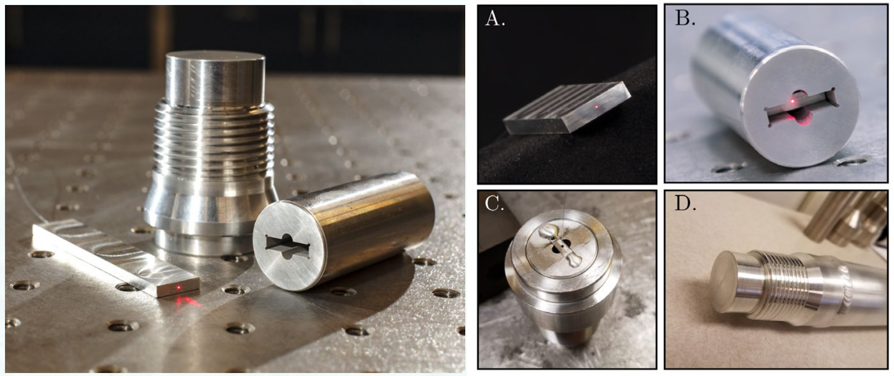
Fiber optics embedded in 3D printed stainless steel (left) or SiC (right) for local strain or vibration monitoring [1, 2]



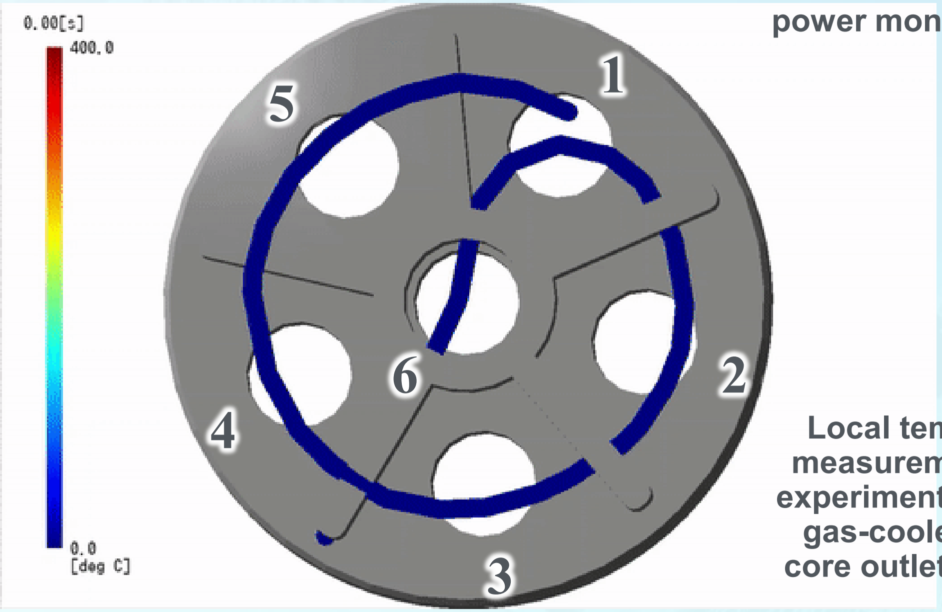
Rad-hard Front End Digitizer (FREND) to transmit conventional sensor data through reactor containment over fiber optic cables to reduce noise in cabling [3]



Distributed gamma thermometer (local power monitoring) [4]



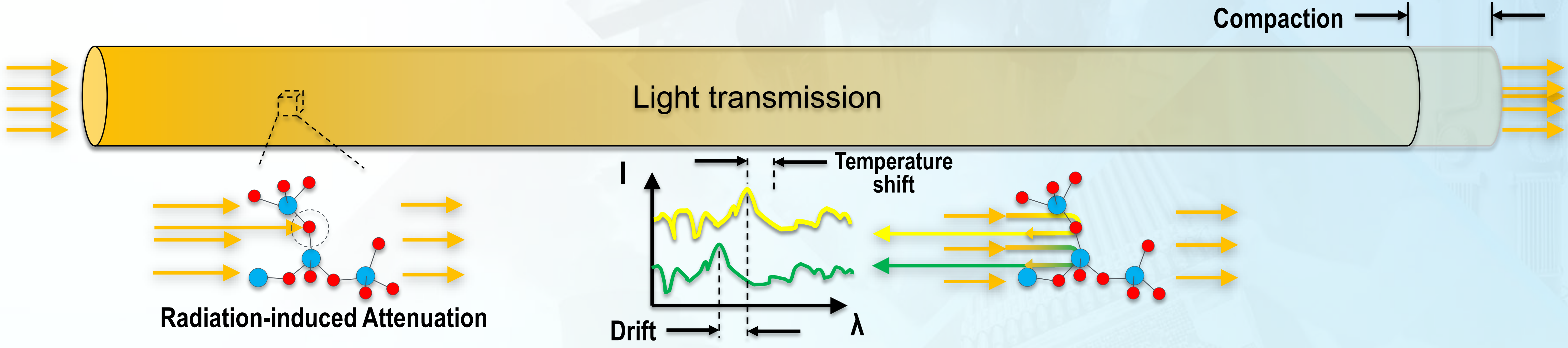
Embedded fiber optic sensor for measuring pressure, corrosion, or acoustic emissions [5, 6]

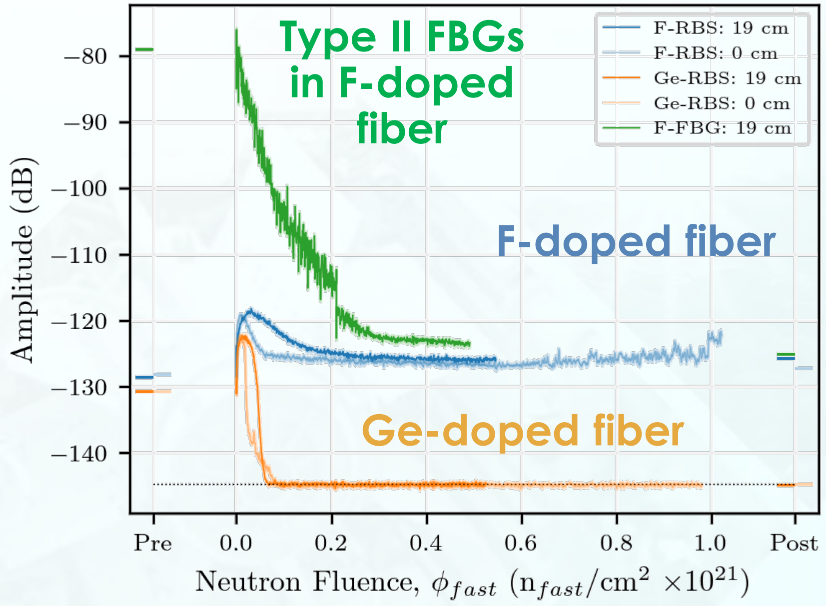


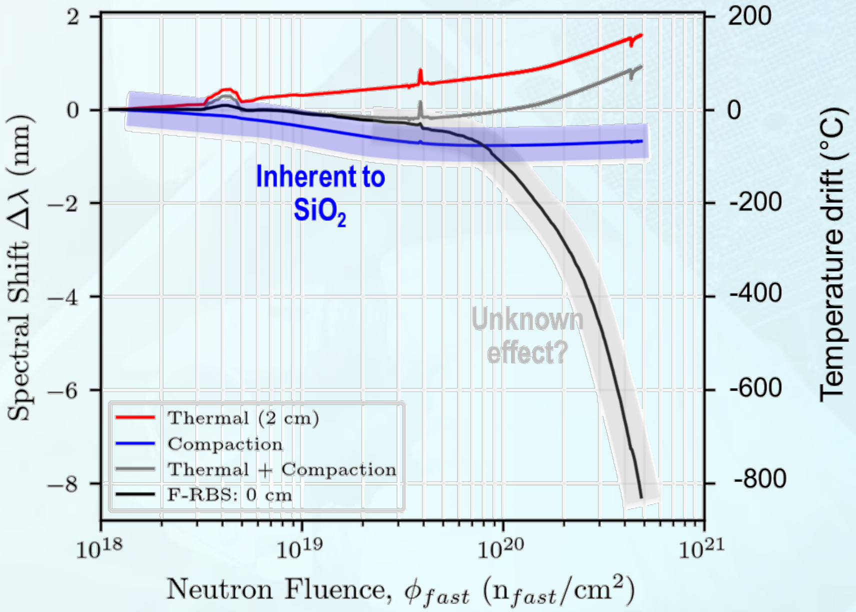
Local temperature measurements in an experiment simulating gas-cooled reactor core outlet mixing [7]

[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] D.C. Sweeney et al., "Analog Front End Digitizer using Optical Pulse-Width Modulation for Nuclear Applications," *IEEE Trans. Instrum. Meas.* (under review)
[4] A. Birri and T.E. Blue, *Progress in Nuclear Energy* **130** (2020) 103552.
[5] D.C. Sweeney, A.M. Schrell, and C.M. Petrie, *IEEE Trans. Instrum. Meas.* **70** (2021) 1-10.
[6] 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.
[7] H.C. Heyer, D.R. Giuliano, and C.M. Petrie, *Appl. Therm. Eng.* **230** (2023) 120847.

How do optical fibers work? What happens under irradiation?

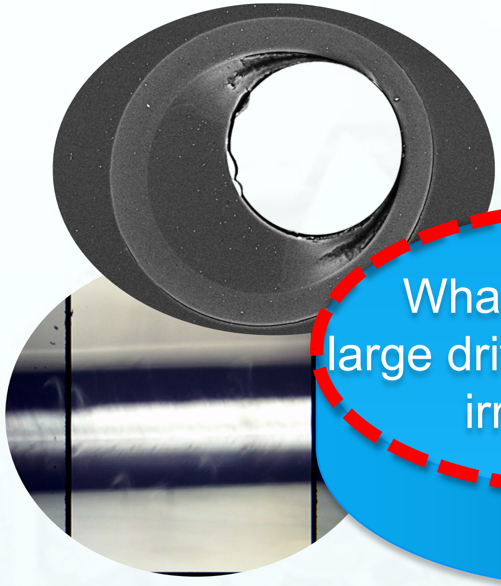






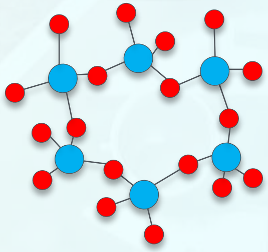
C.M. Petrie and D.C. Sweeney, "Enhanced backscatter and unsaturated blue wavelength shifts in F-doped fused silica optical fibers exposed to extreme neutron radiation damage", *J. Non-Cryst. Solids* **615** (2023) 122441 doi.org/10.1016/j.jnoncrysol.2023.122441

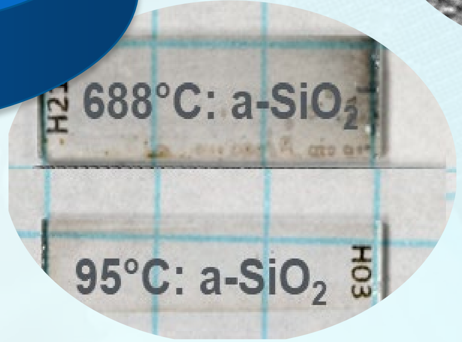
What problems are we trying to solve?



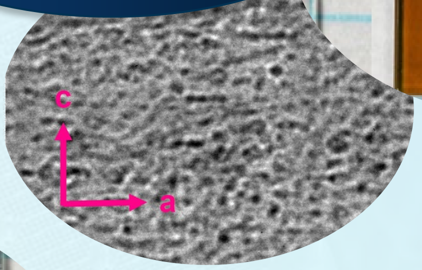
What caused the large drift we see during irradiation?

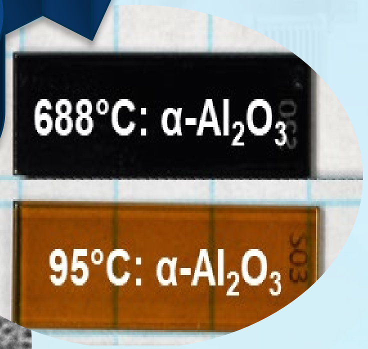
Do we understand radiation-induced structural changes in SiO_2?



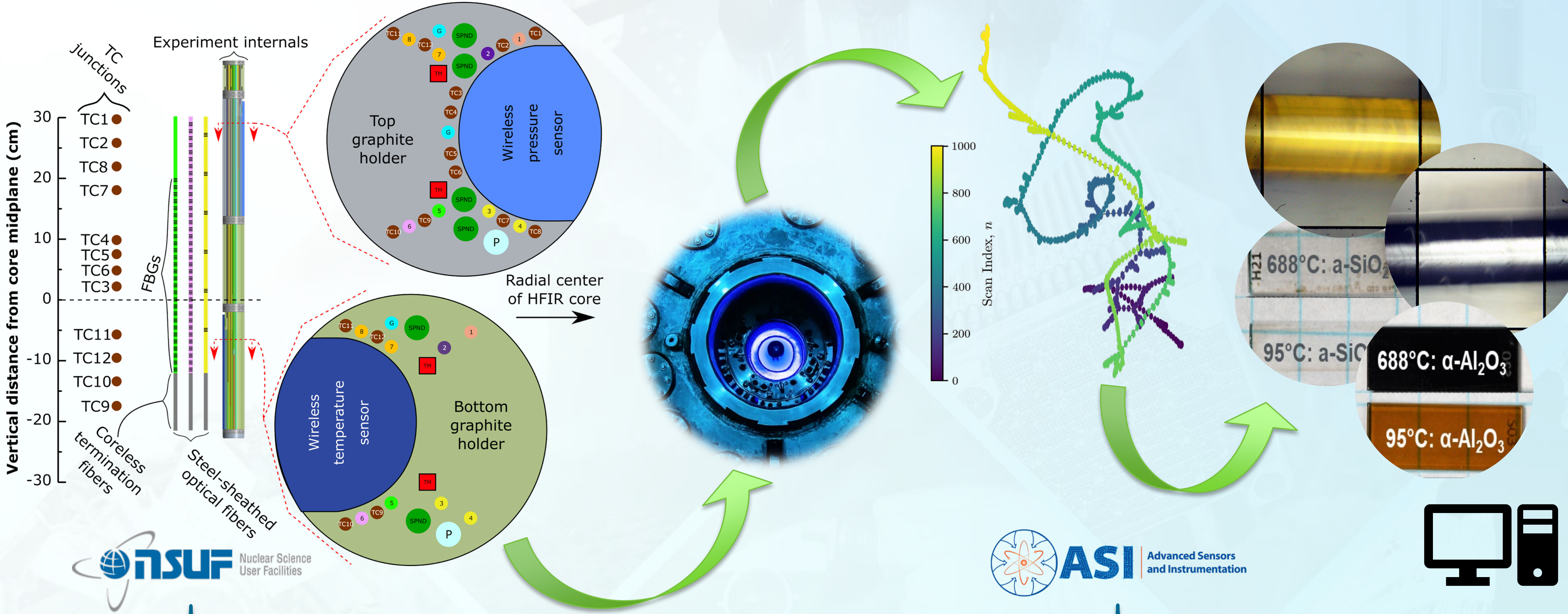


Are sapphire fibers an option in-core at >1,000°C?





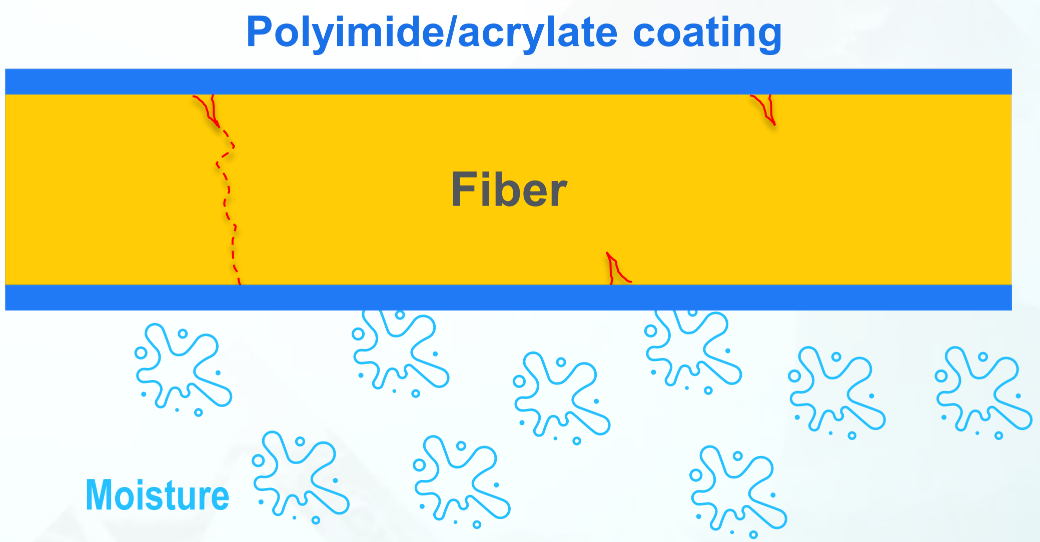
It takes a long time to understand the results from complex HFIR or ATR irradiation experiments



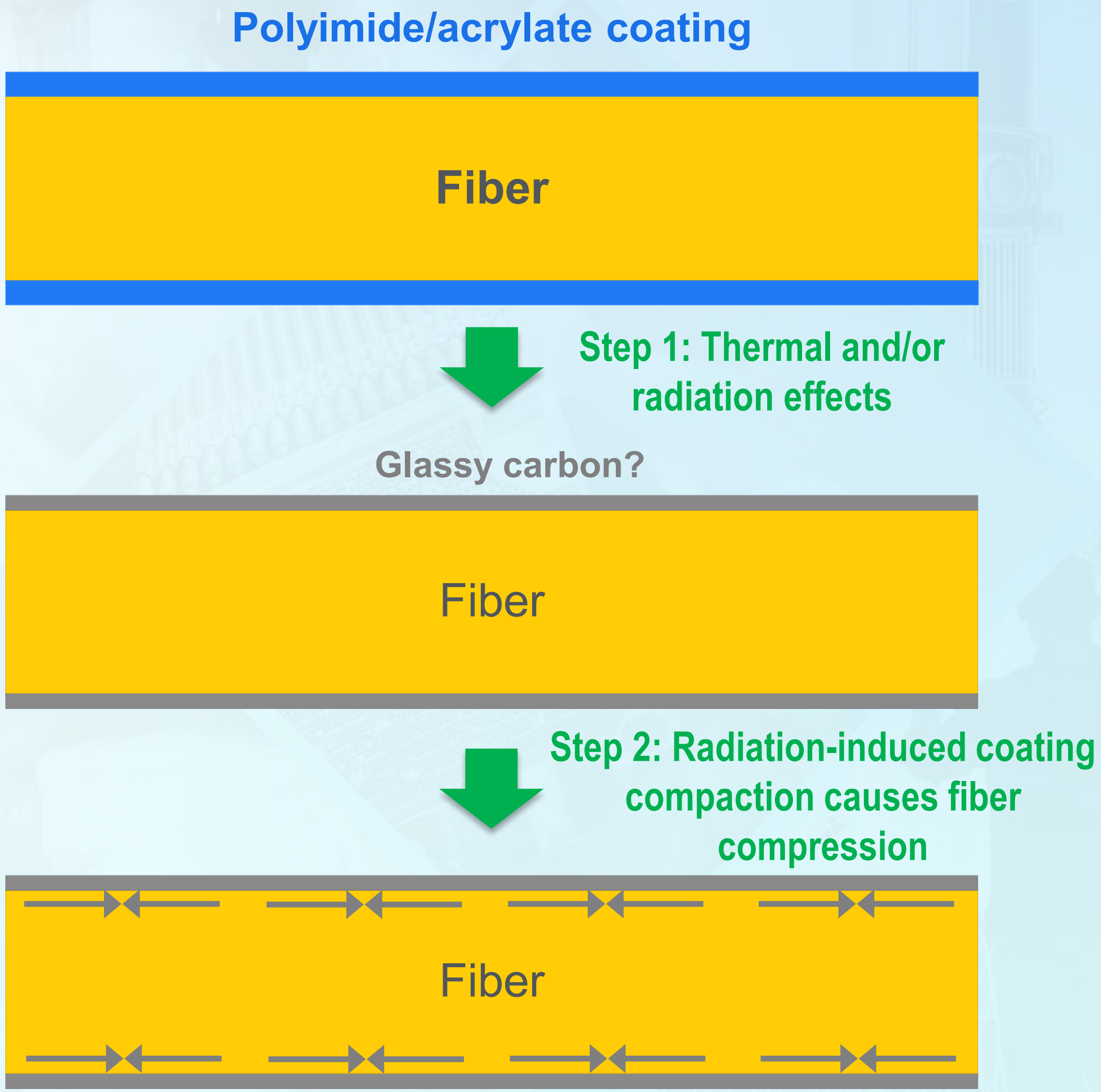
FY20				FY21				FY22				FY23				FY24			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WIRE-21 experiment design					Fabrication		Assembly		Irradiation			Data analysis				Modeling/testing/PIE			

Hypothesis: Coating decomposition + radiation-induced compaction resulted in significant compressive strain on the fiber

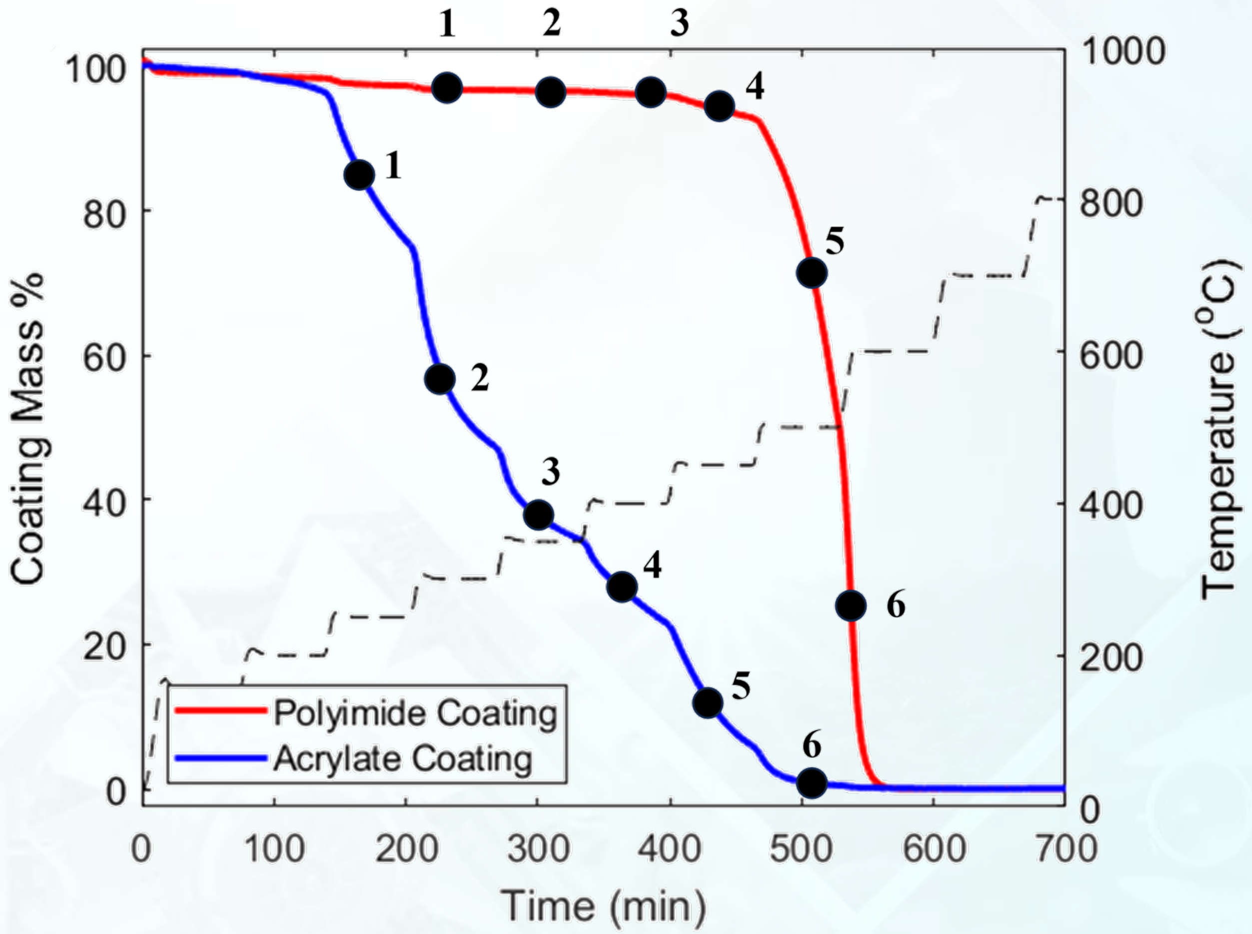
Coatings are necessary to protect the fiber during handling

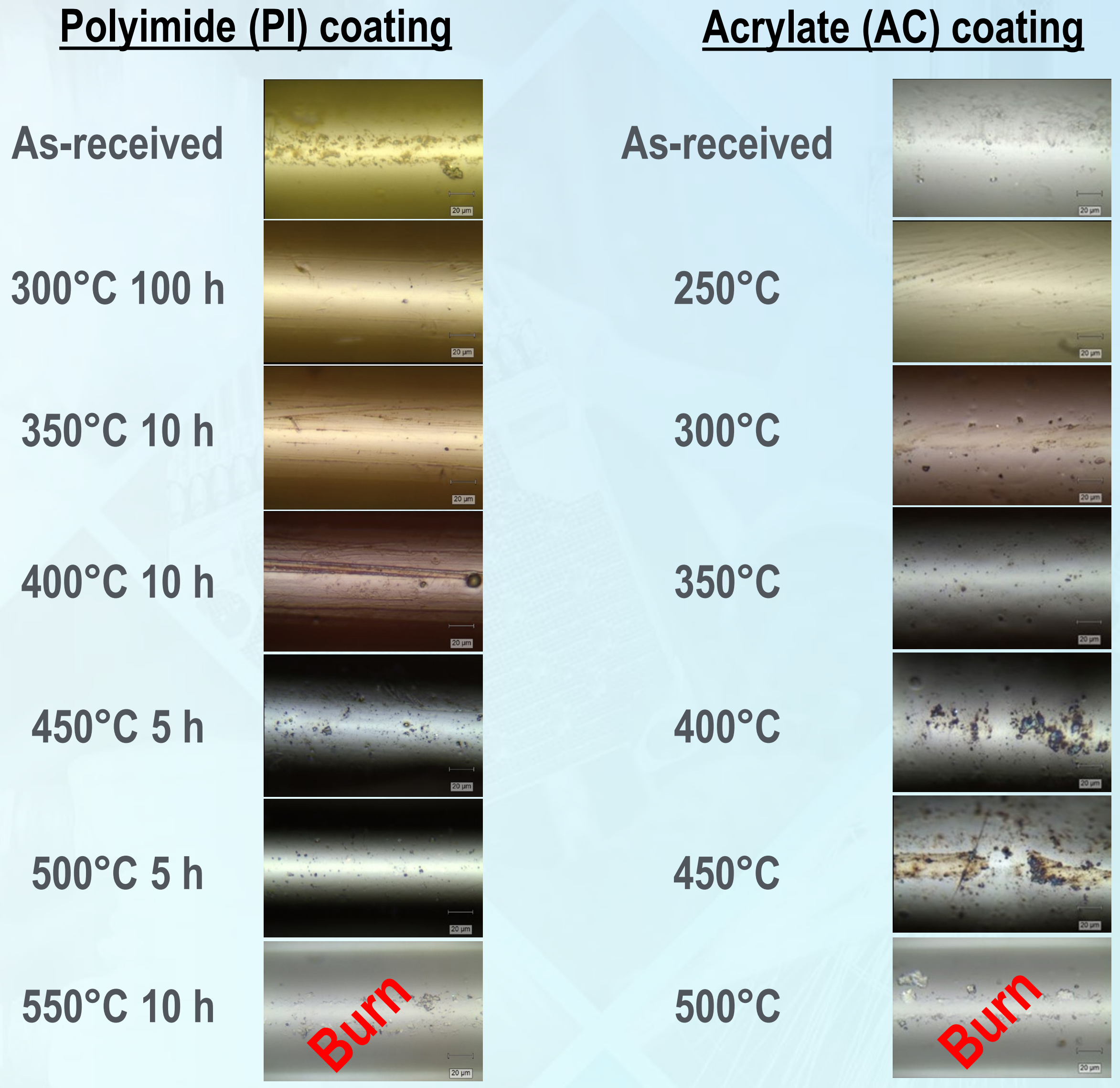


Common assumption: Polymeric coatings are too weak to affect the fiber or they burn off

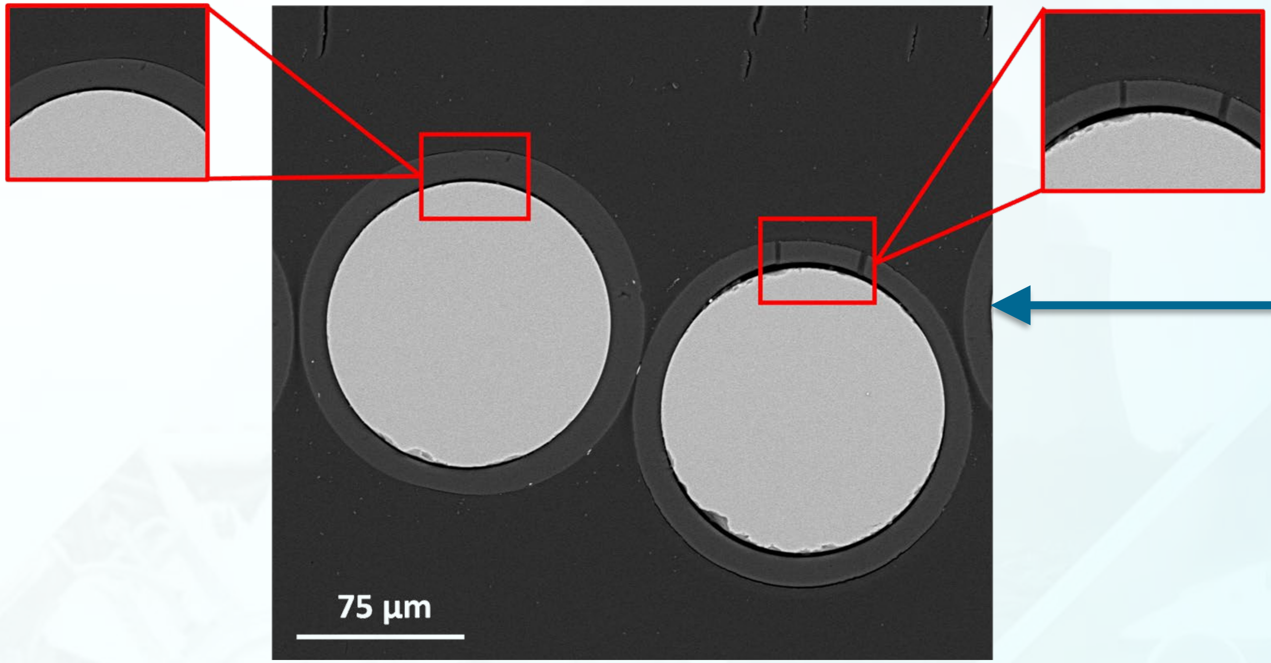


Polyimide and acrylate coatings thermally decompose in air at temperatures of ~400° C or below and turn matte-black





Just because there is a matte black (carbon?) coating, doesn't mean it can transfer strain to the fiber



Polyimide (PI) coating

As-received

300°C 100 h

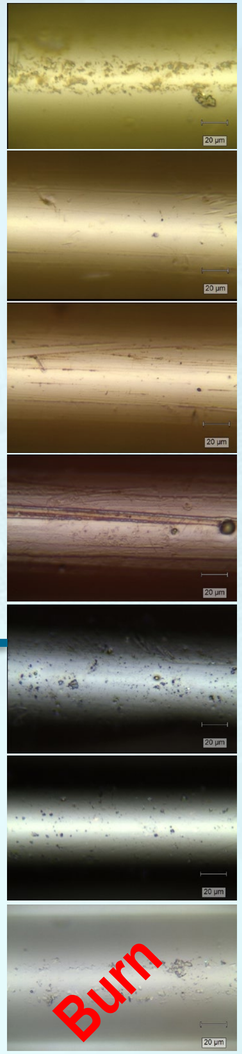
350°C 10 h

400°C 10 h

450°C 5 h

500°C 5 h

550°C 10 h



Acrylate (AC) coating

As-received

250°C

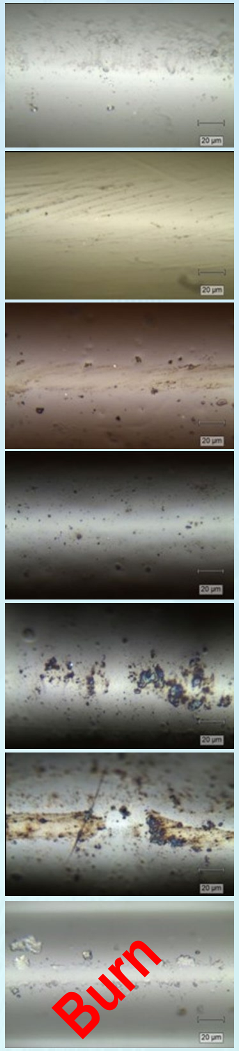
300°C

350°C

400°C

450°C

500°C



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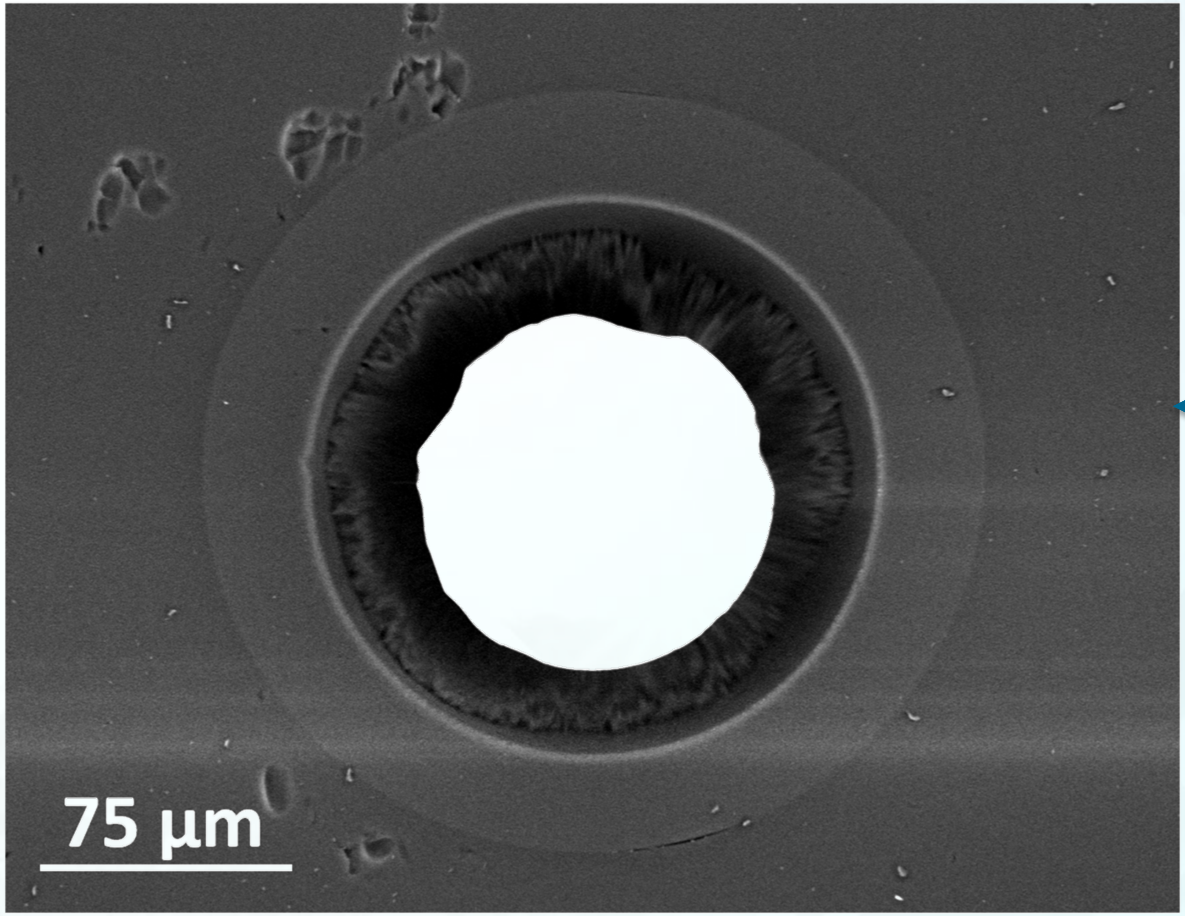

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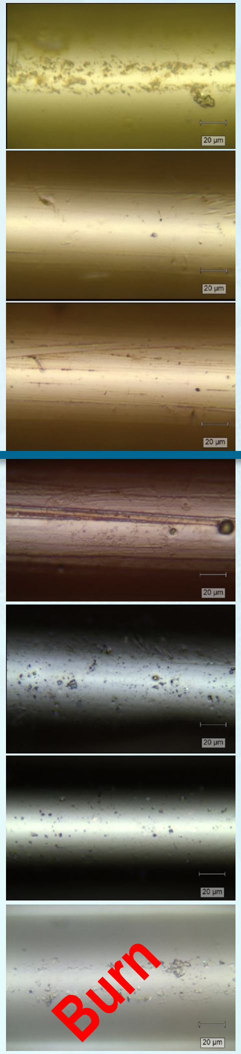

Acrylate (AC) coating

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300°C
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400°C
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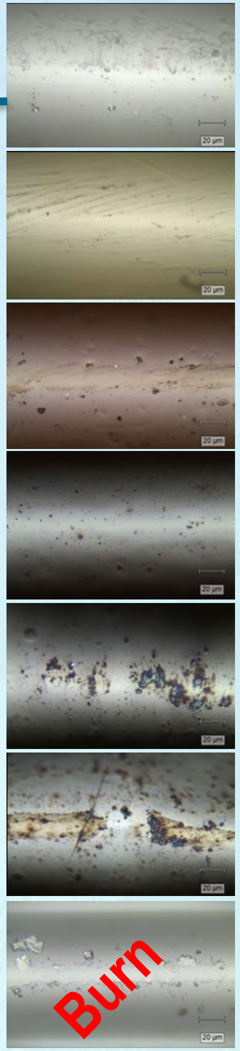
500°C



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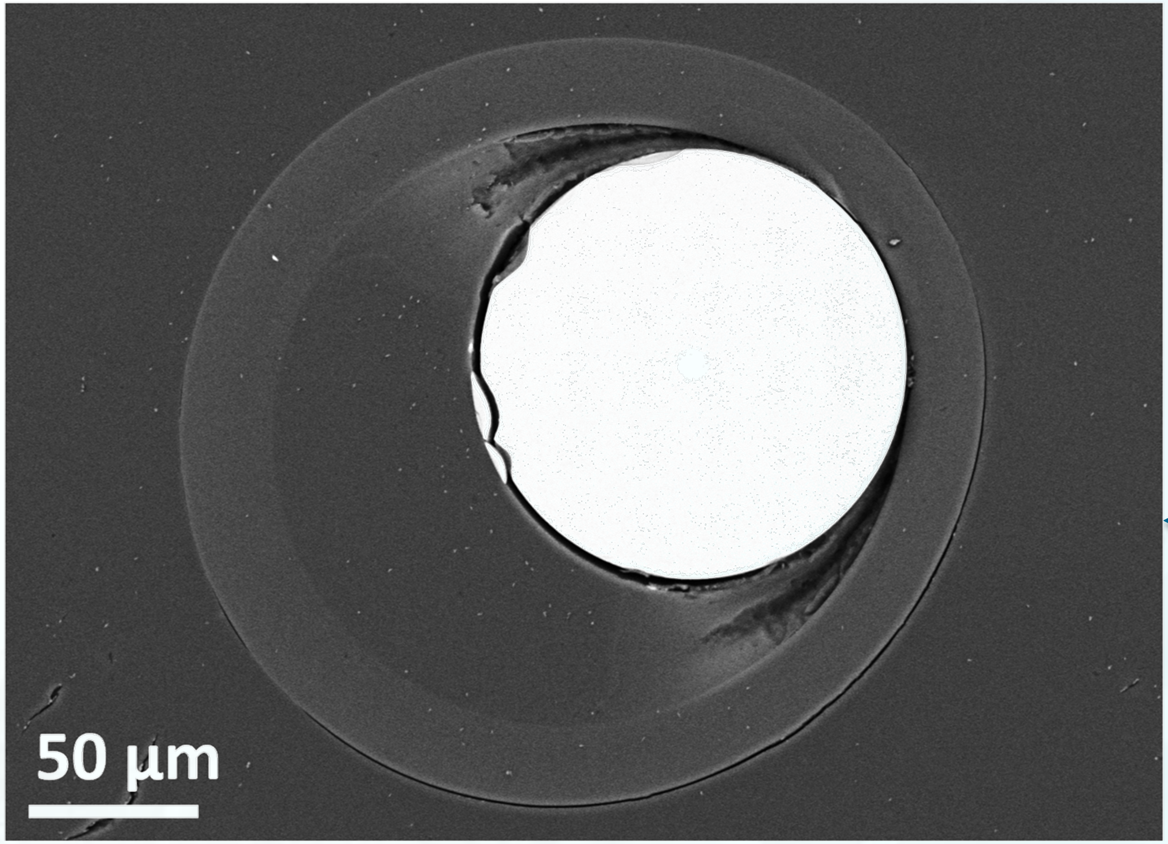

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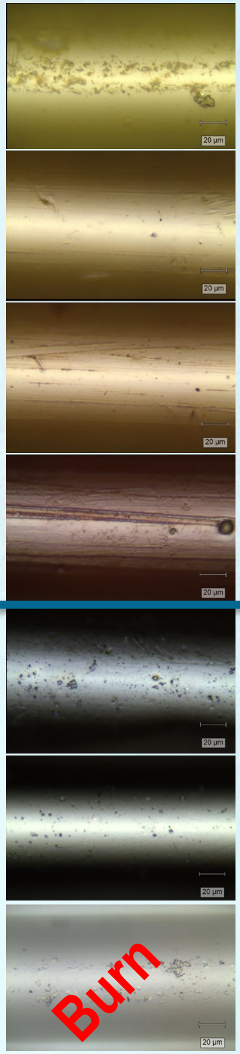

Acrylate (AC) coating

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300°C
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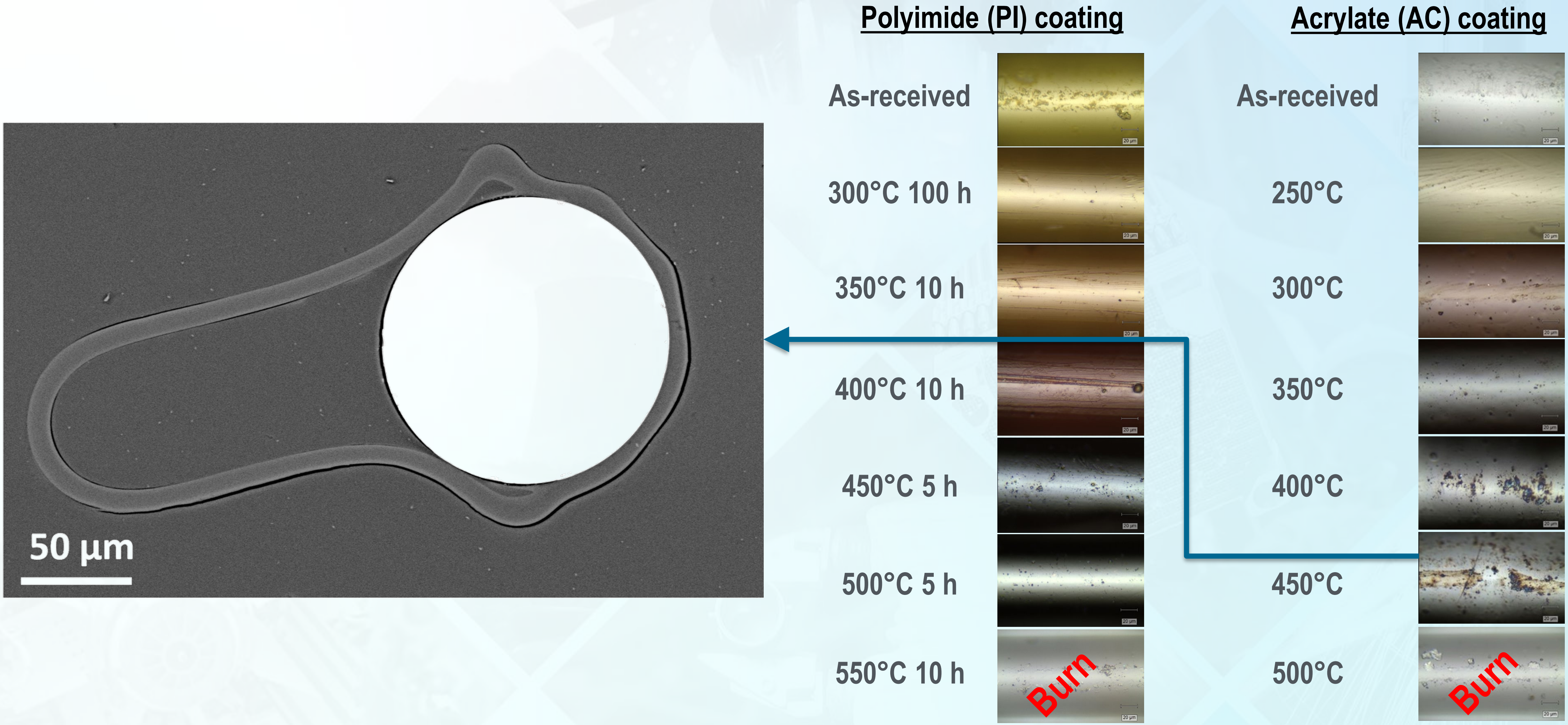
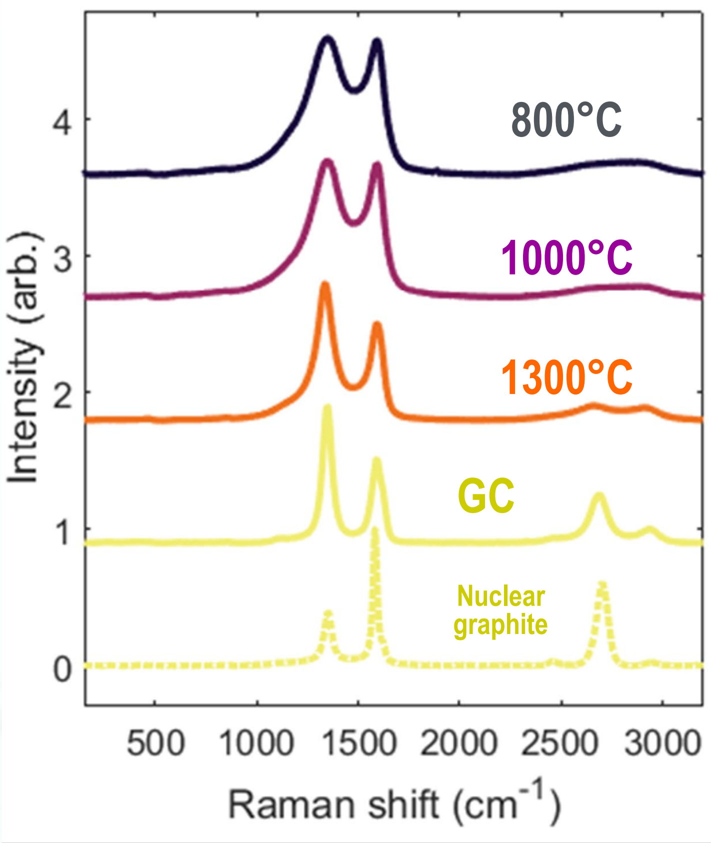
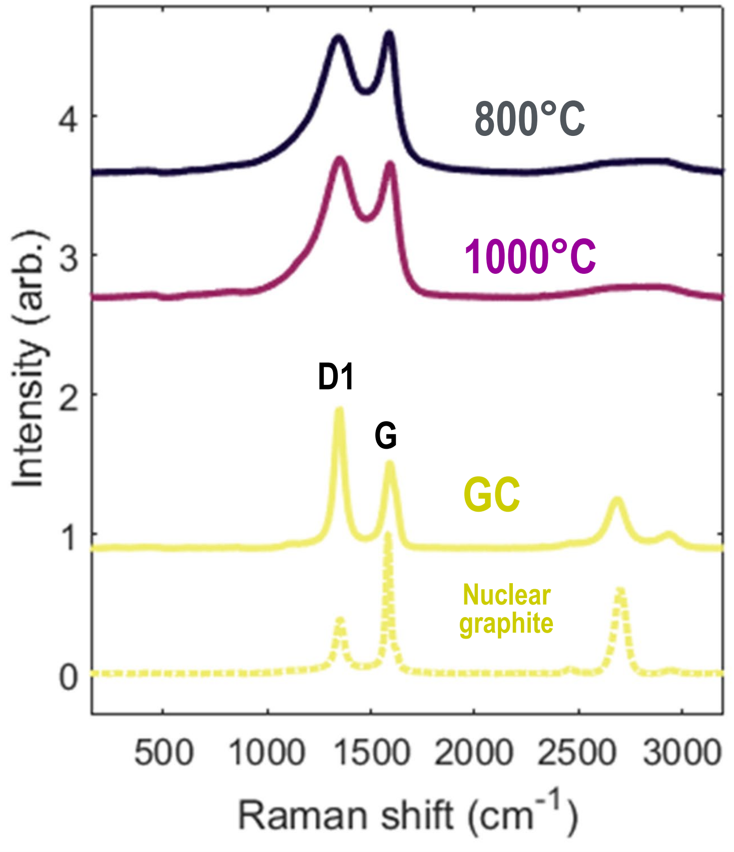


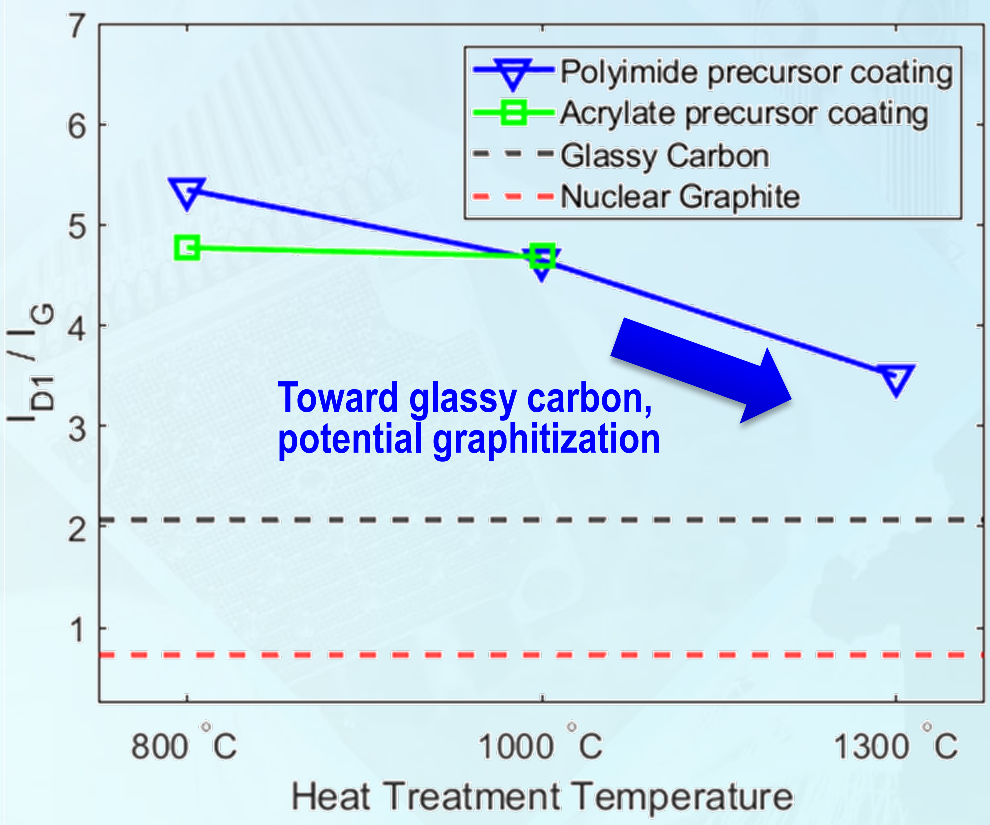
Under inert conditions, both coatings form glassy carbon (GC)…

Polyimide (PI)

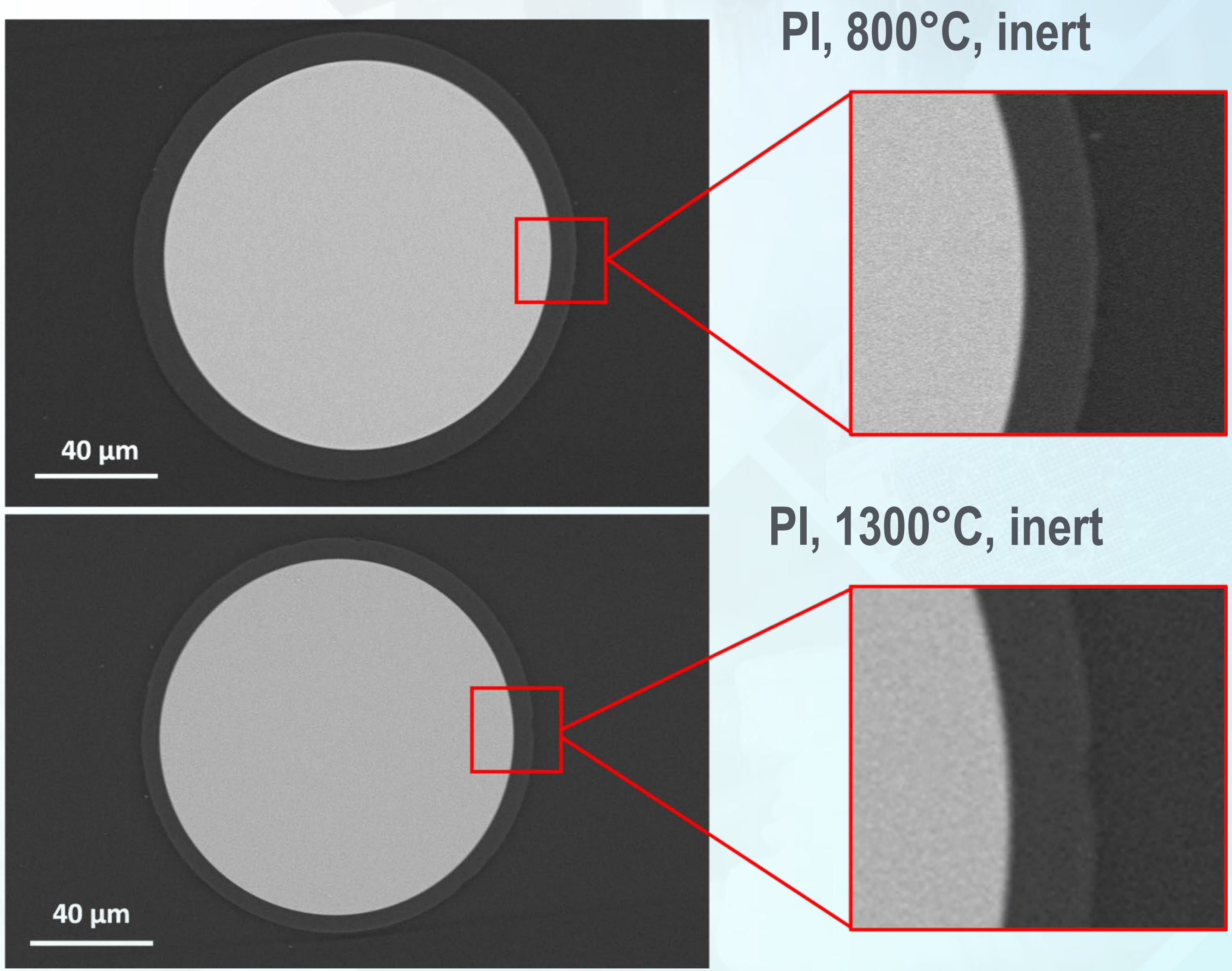


Acrylate (AC)

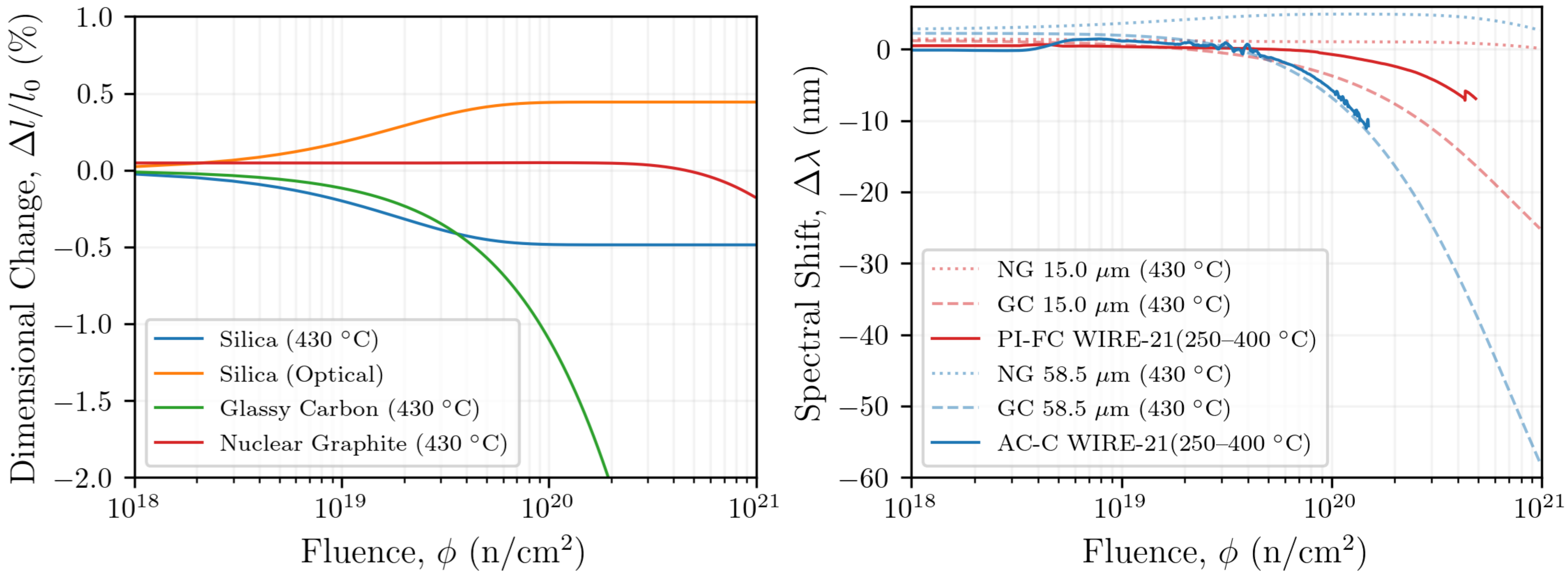




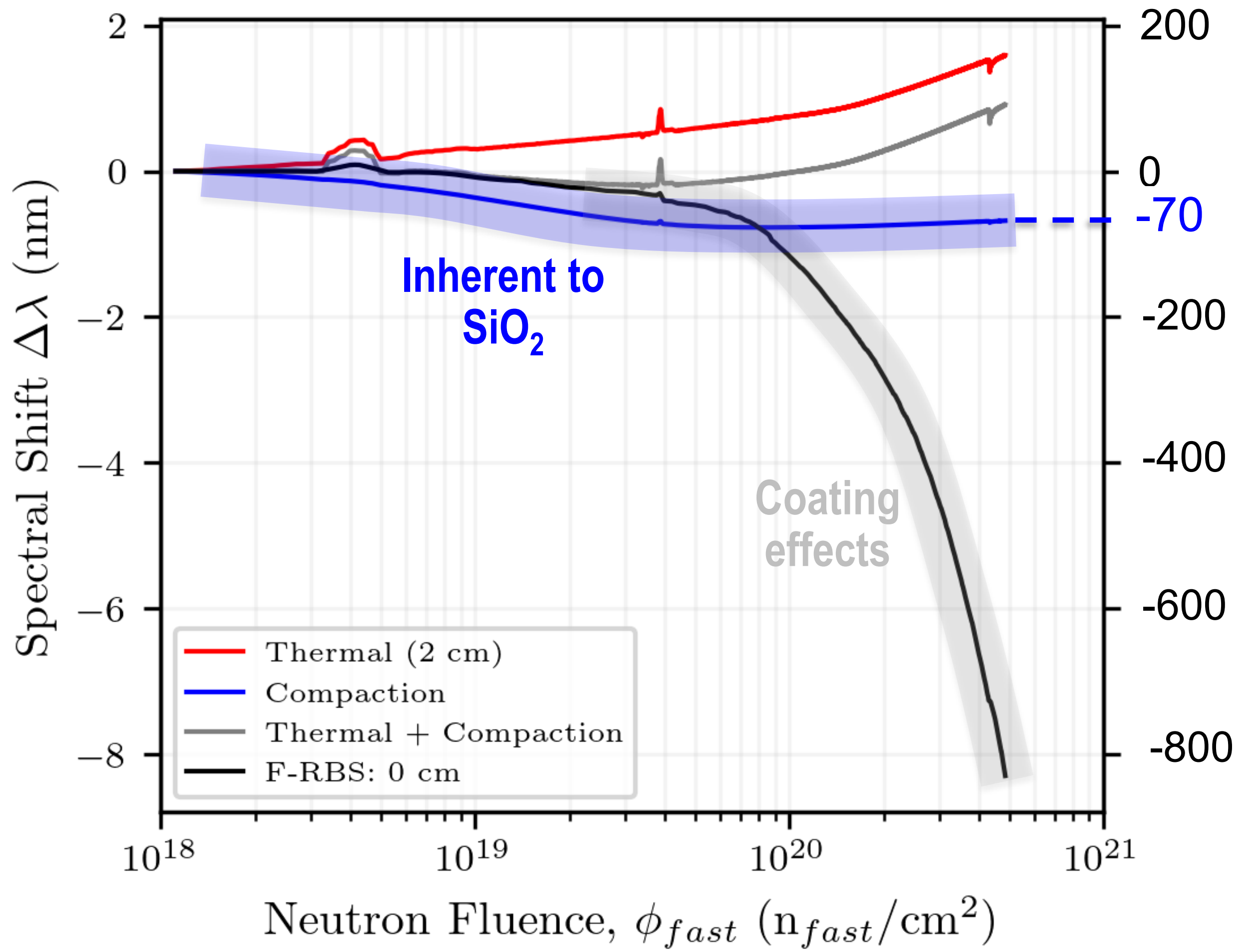
…and remain well-adhered to the fiber



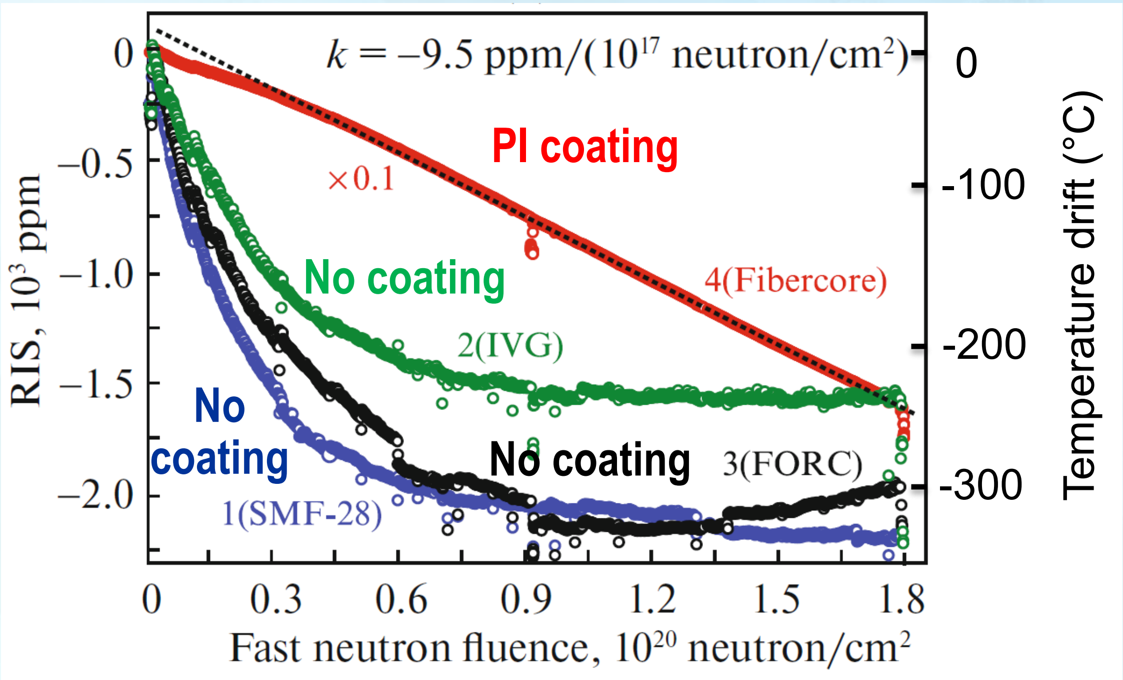
Models predict that glassy carbon compaction can induce strains that generally match WIRE-21 fiber optic shift data



Let's just remove the coating! … Doesn't entirely solve the problem



C.M. Petrie and D.C. Sweeney, "Enhanced backscatter and unsaturated blue wavelength shifts in F-doped fused silica optical fibers exposed to extreme neutron radiation damage", *J. Non-Cryst. Solids* **615** (2023) 122441 doi.org/10.1016/j.jnoncrysol.2023.122441

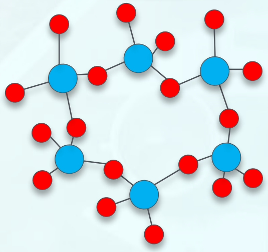


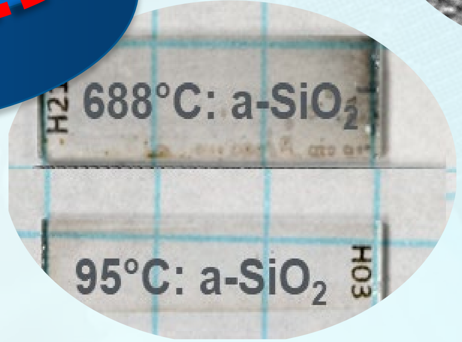
P.F. Kashaykin et al., "Radiation Resistance of Fiber Bragg Gratings under Intense Reactor Irradiation", *Bull. Lebedev Phys. Inst.* **50** (2023) S322 doi.org/10.3103/S1068335623150071

What problems are we trying to solve?

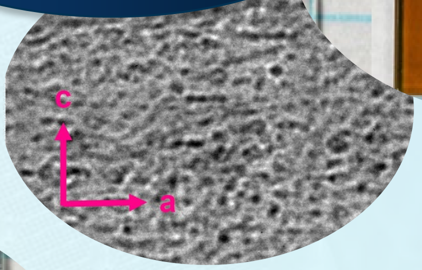
What caused the large drift we see during irradiation?

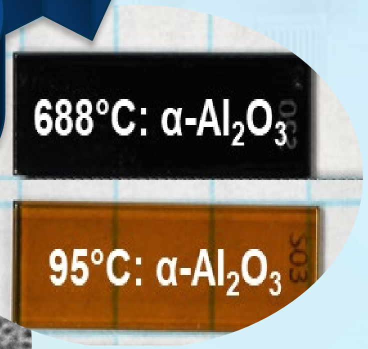
Do we understand radiation-induced structural changes in SiO_2?



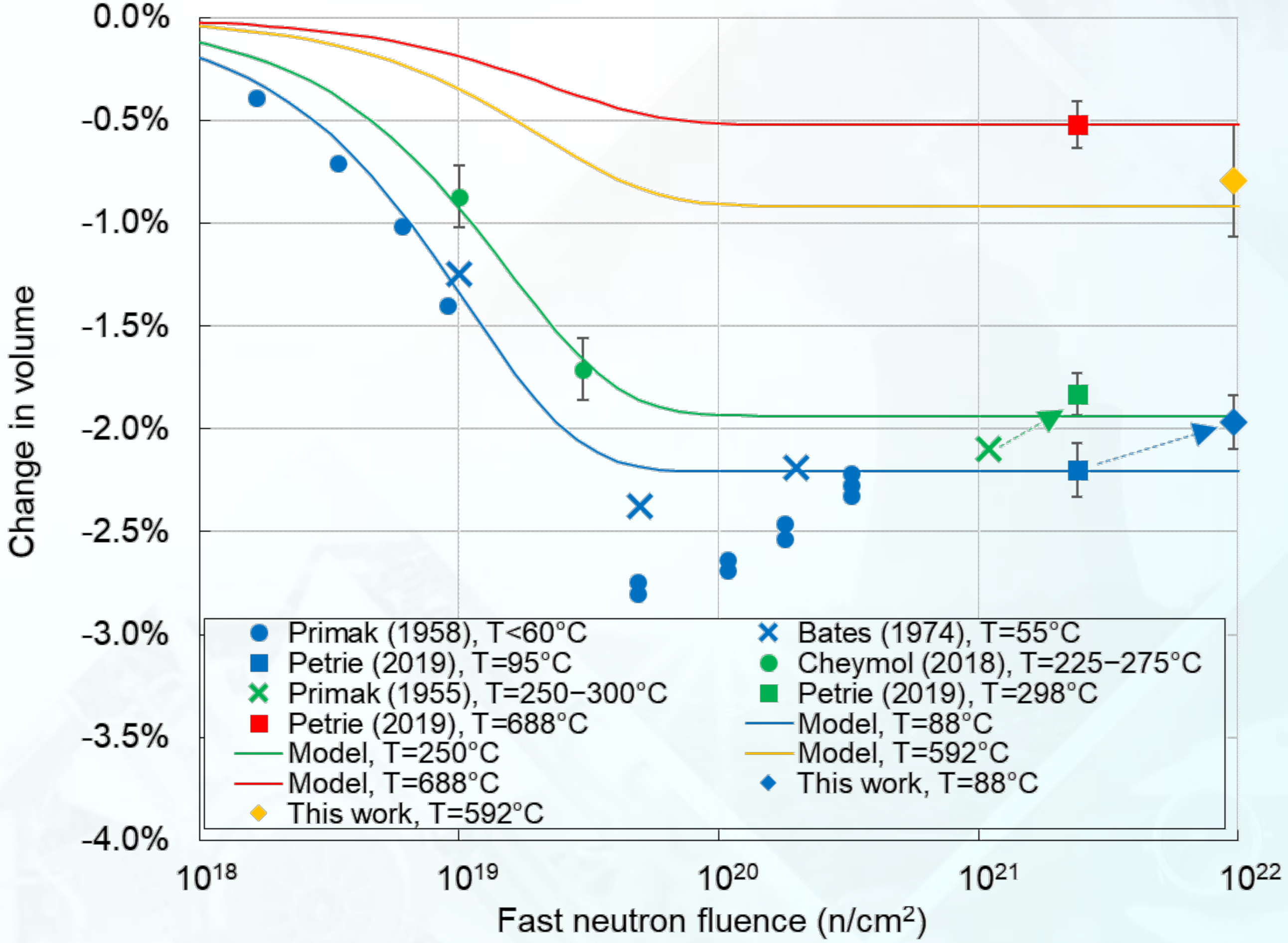


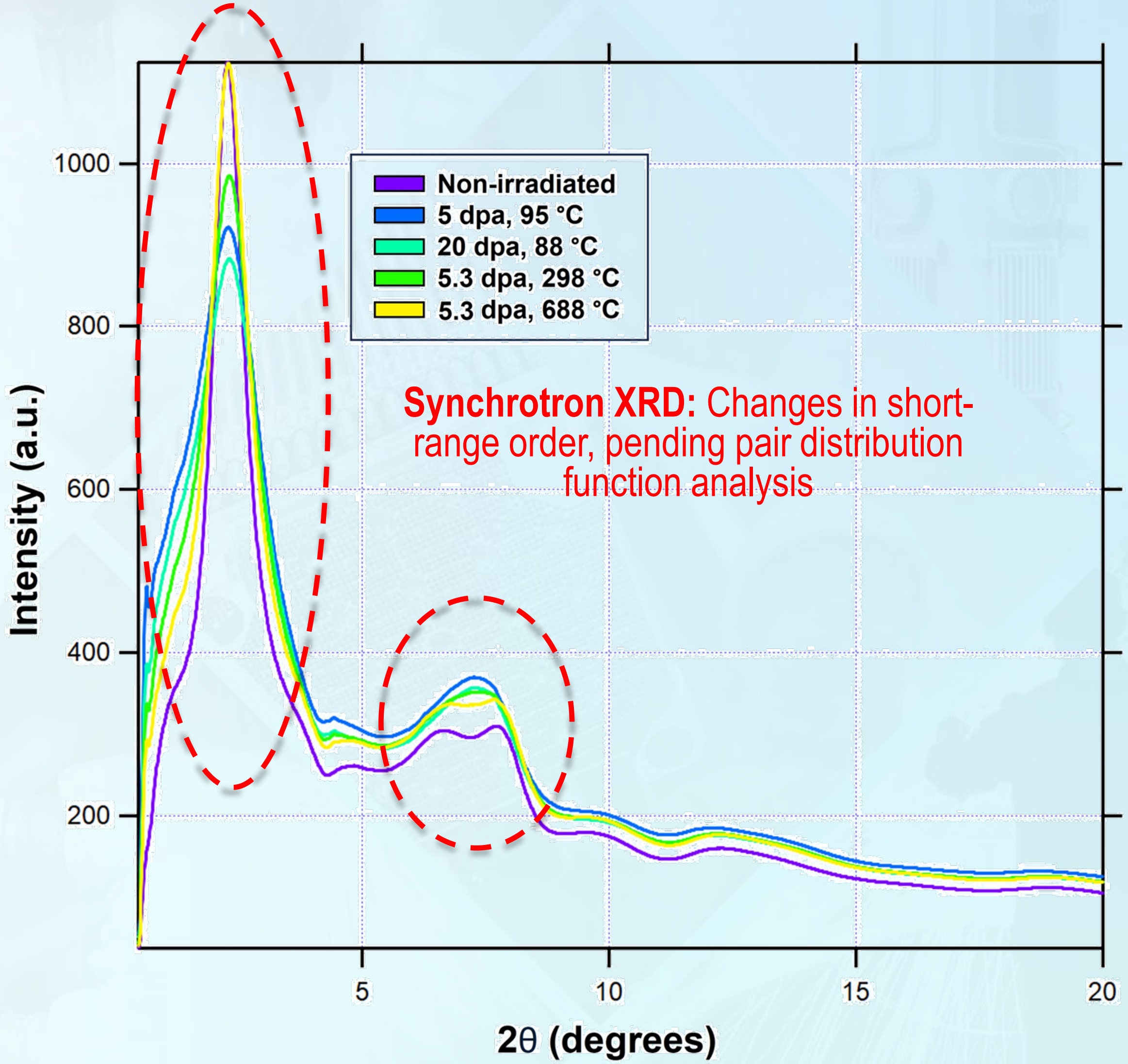
Are sapphire fibers an option in-core at >1,000°C?



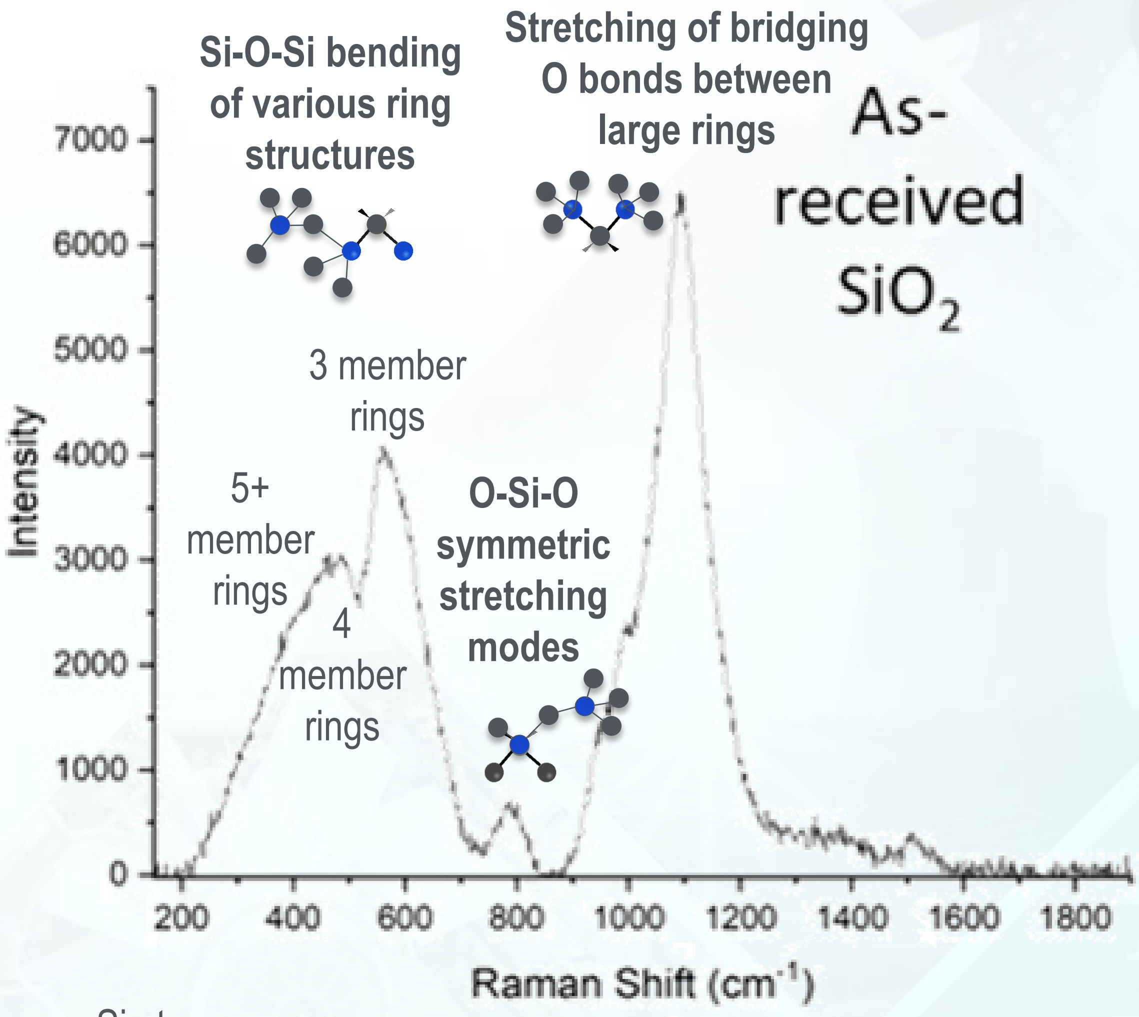


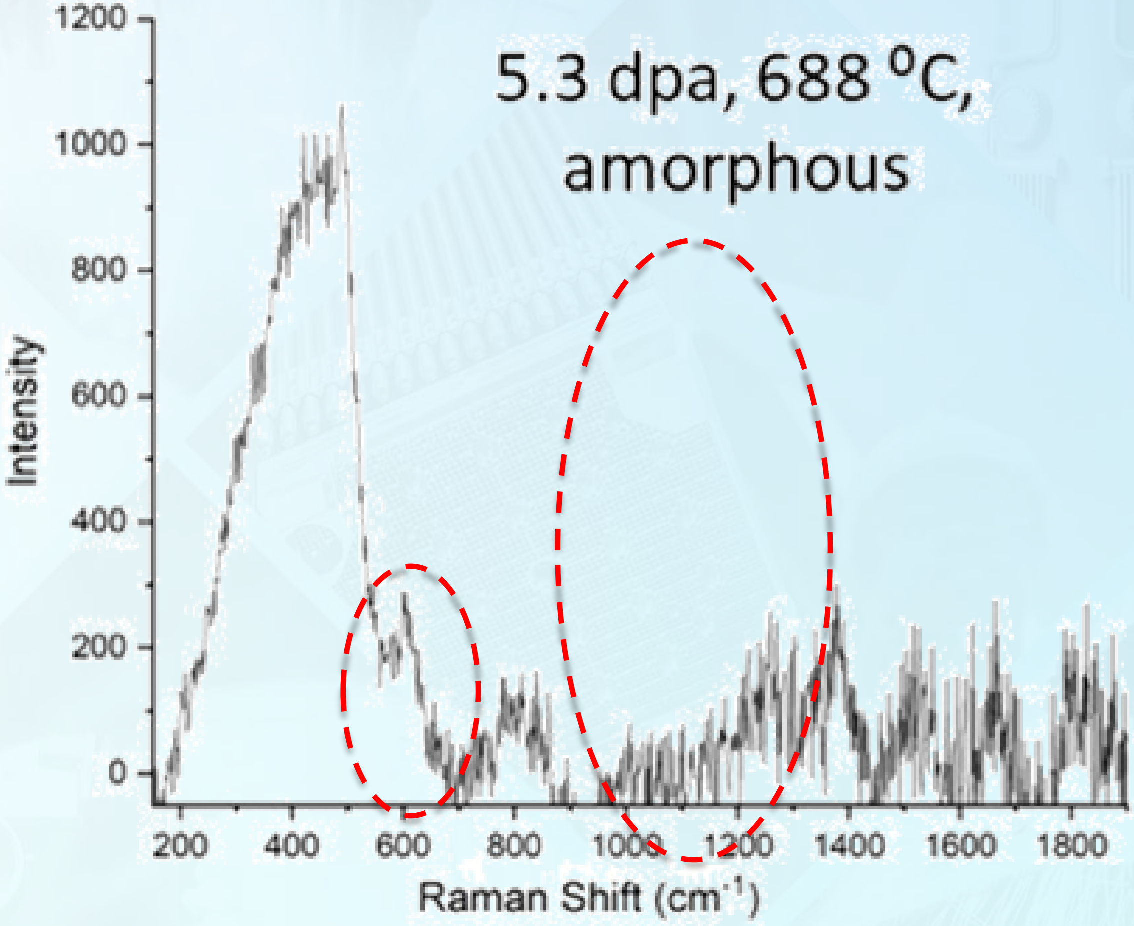
Radiation-induced compaction in fused silica is more complicated than we realized: <u>The models do not capture all the physics</u>





Raman: Irradiation changes ring structures and Si-O-Si angles

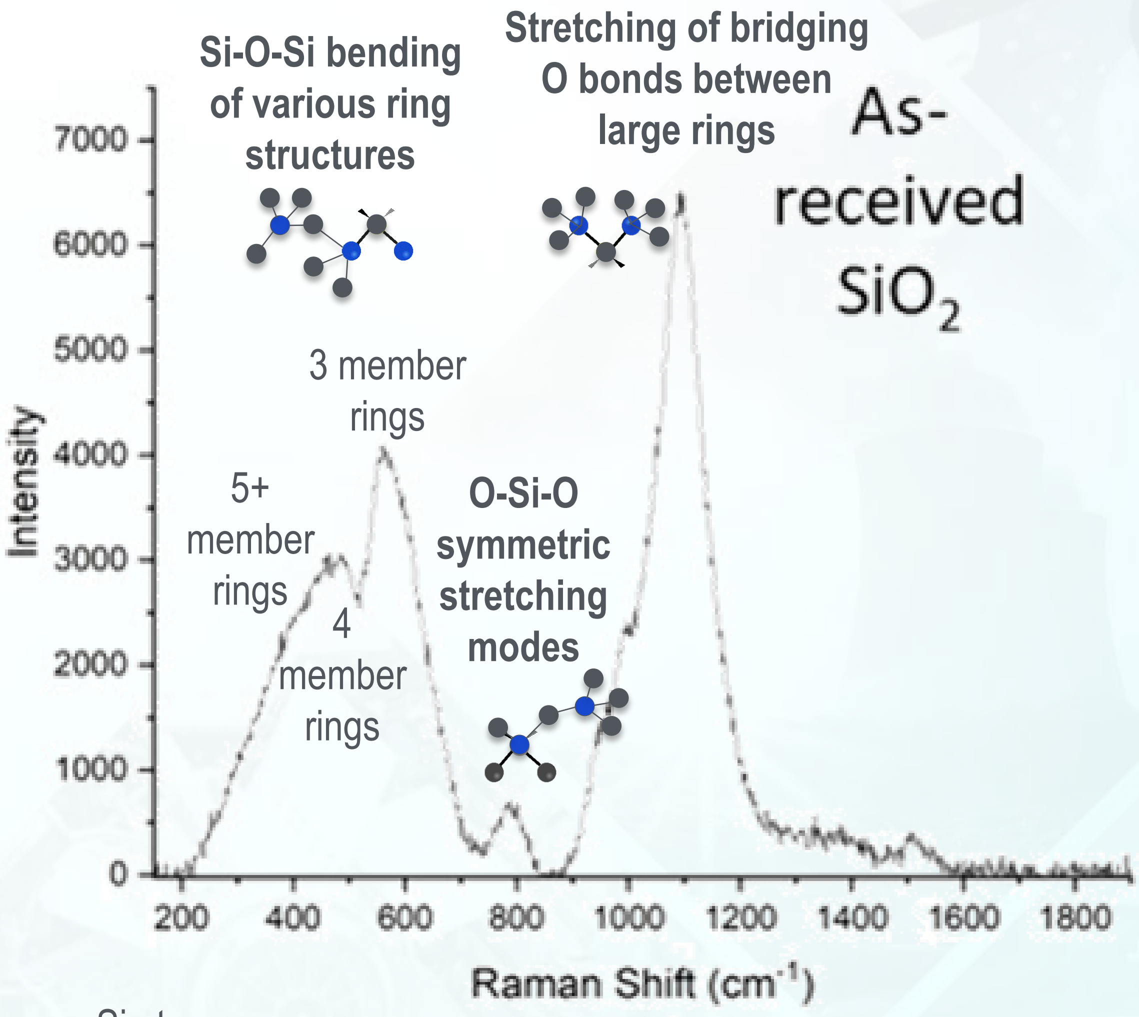


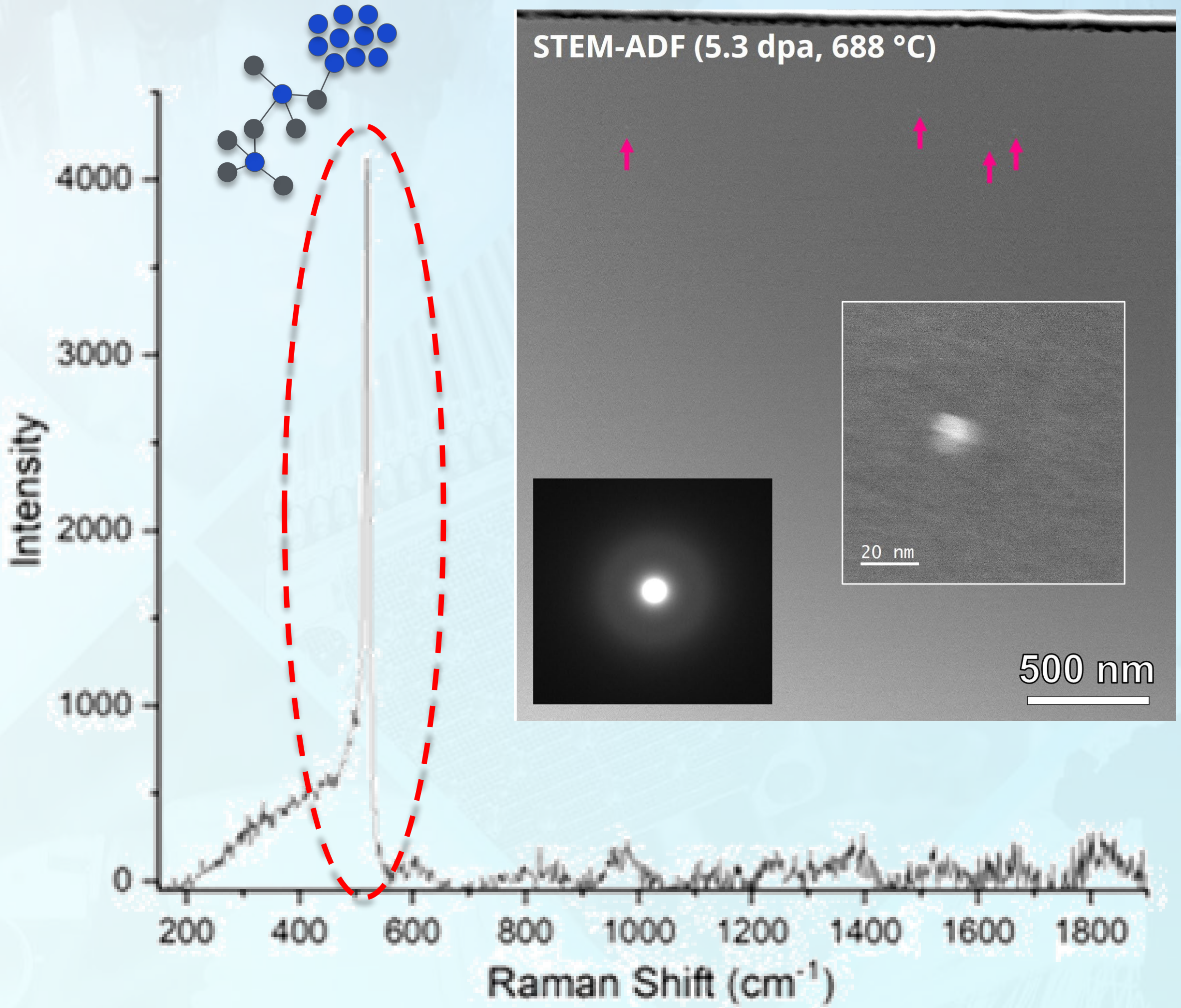


- Si atom
- O atom

Animations taken from:
https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Spectroscopy/Vibrational_Spectroscopy/Vibrational_Modes/Number_of_Vibrational_Modes_in_a_Molecule

Same sample, different area (heterogenous): Nanocrystalline Si

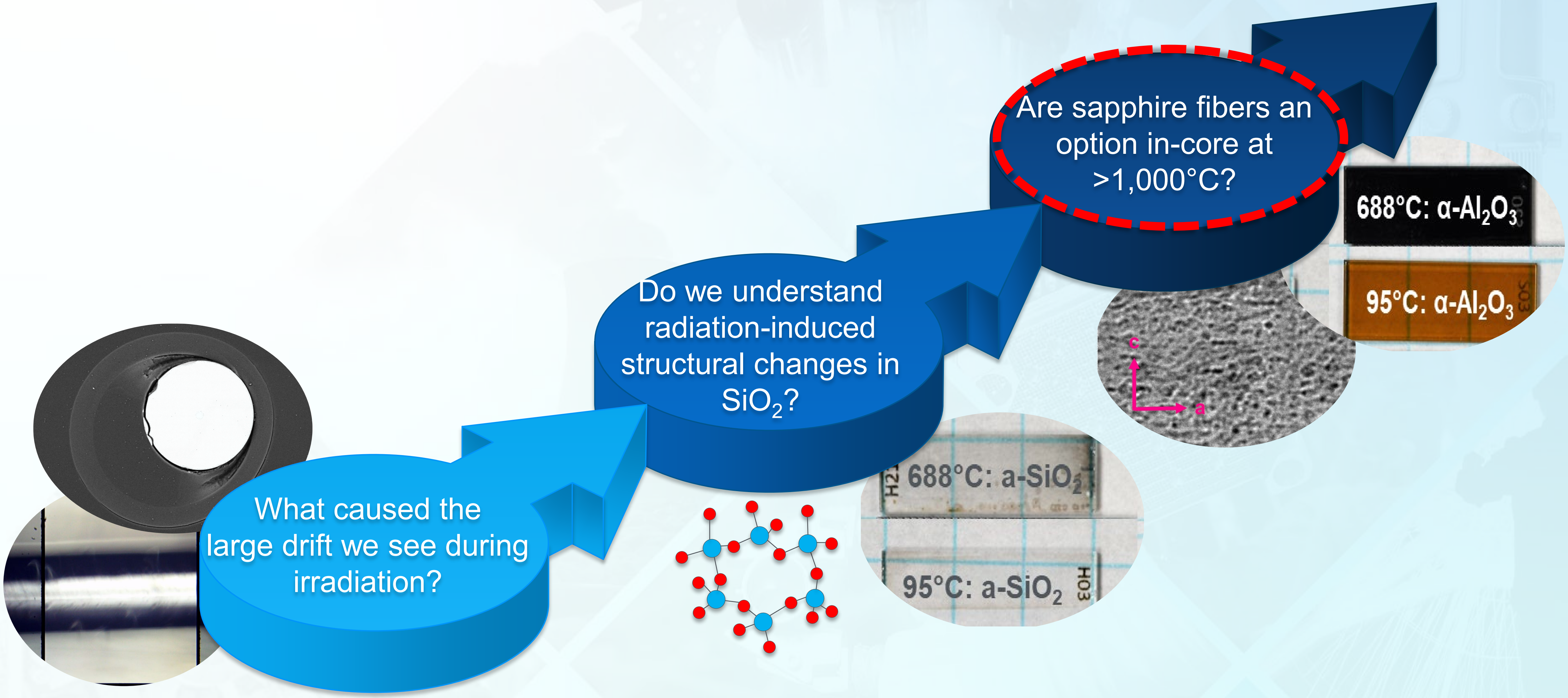




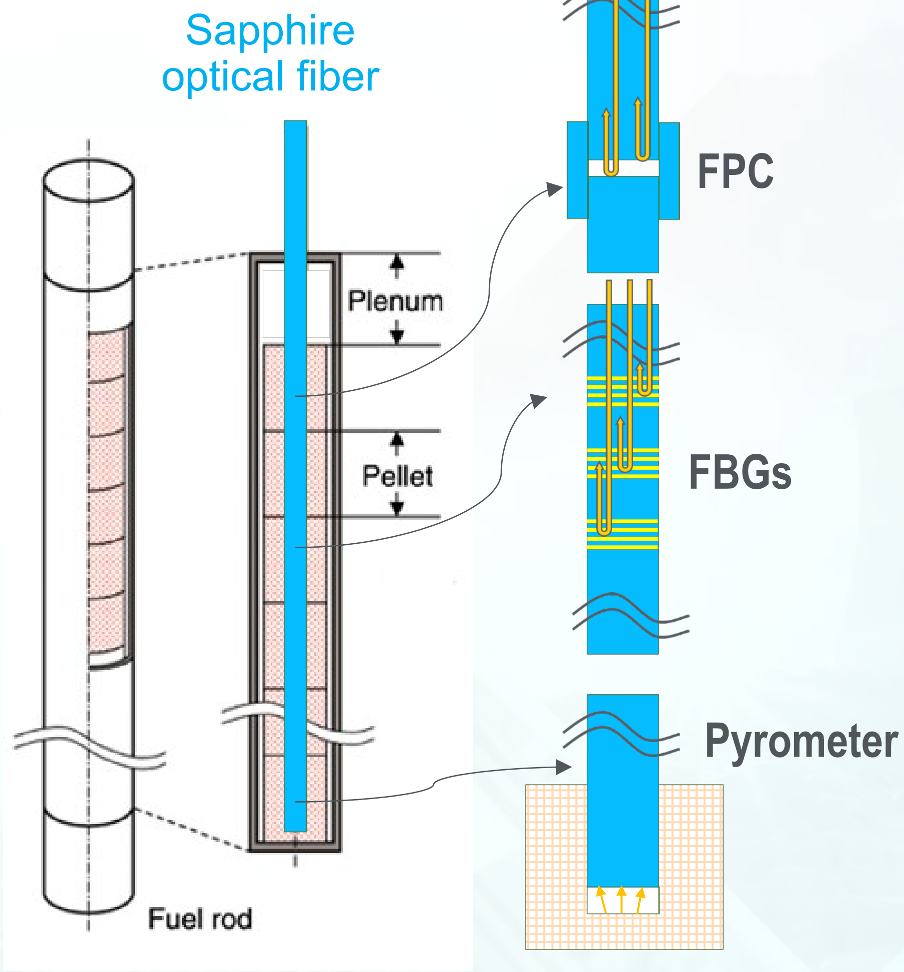
- Si atom
- O atom

Incomplete story, needs more detailed analysis of Raman & XRD spectra

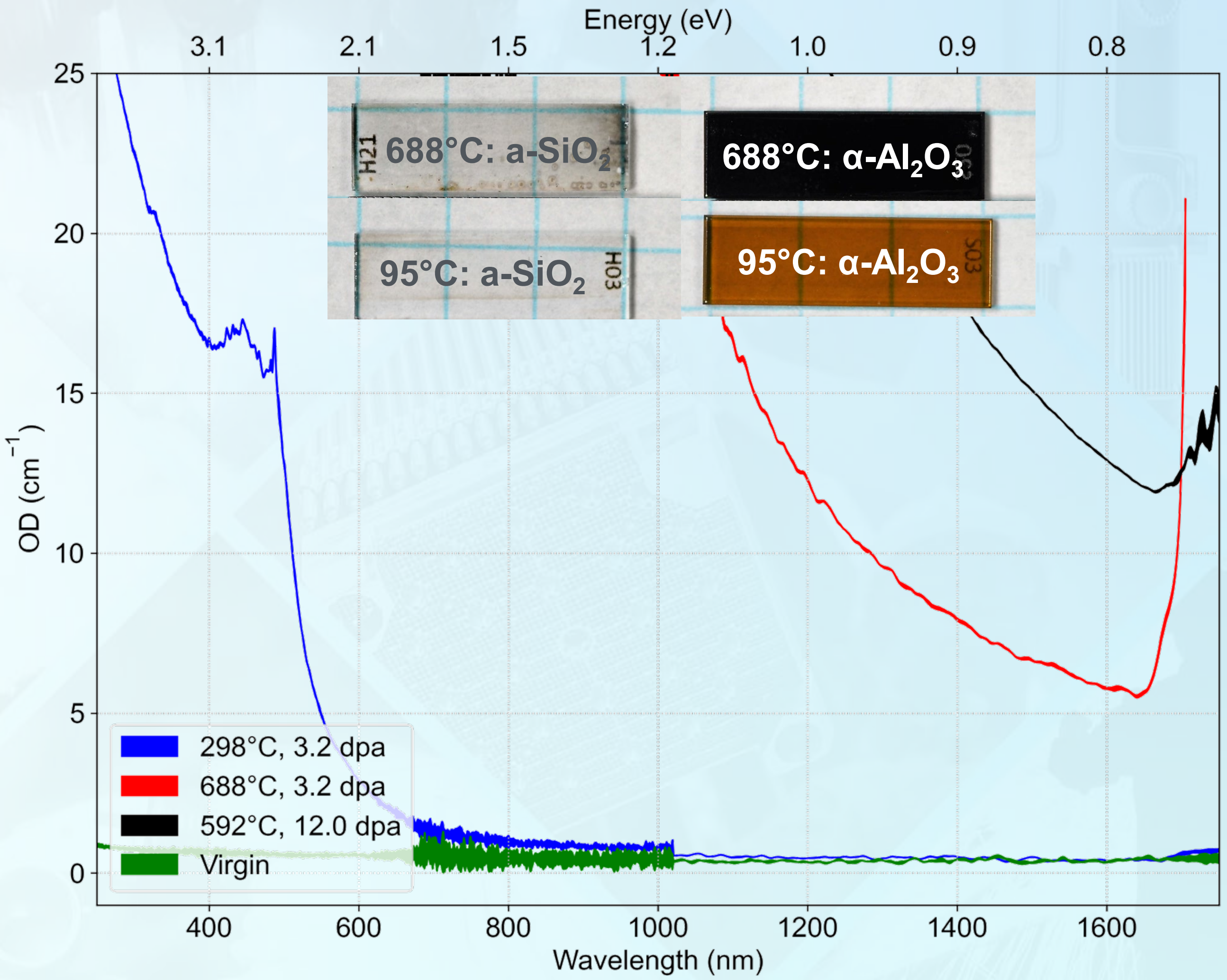
What problems are we trying to solve?



What about sapphire? Will that solve our problems and allow operation at even higher temperatures?

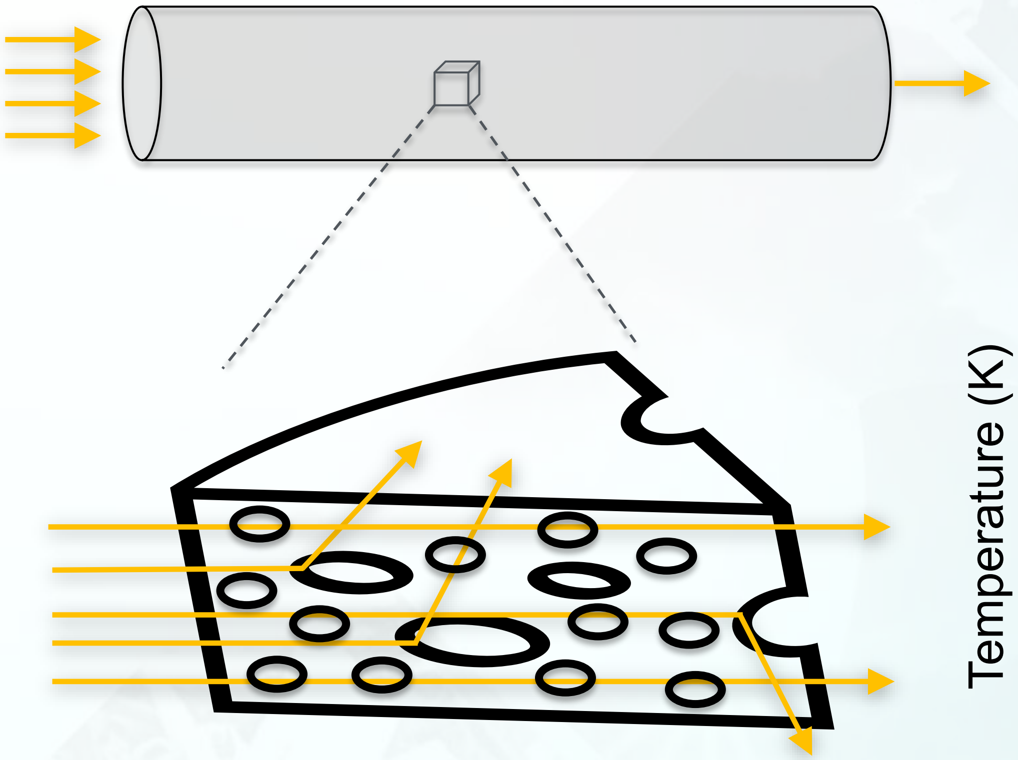


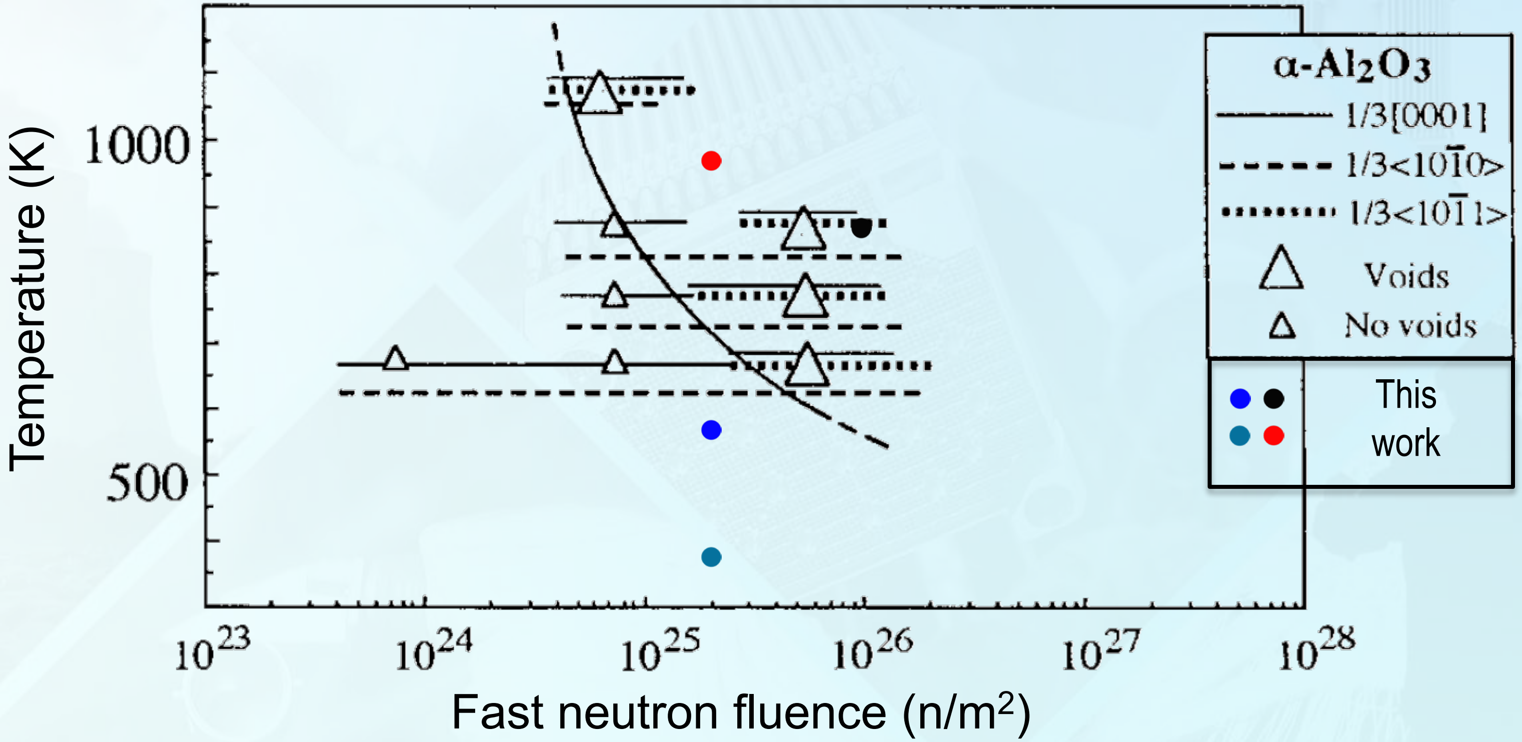
Fuel rod images adapted from http://jolisfukyu.tokai-sc.jaea.go.jp/fukyu/mirai-en/2010/img/honbun/6-4.jpg



C.M. Petrie et al., "Optical transmission and dimensional stability of single-crystal sapphire after high-dose neutron irradiation at various temperatures up to 688°C," *Journal of Nuclear Materials* **559** (2022) 153432.

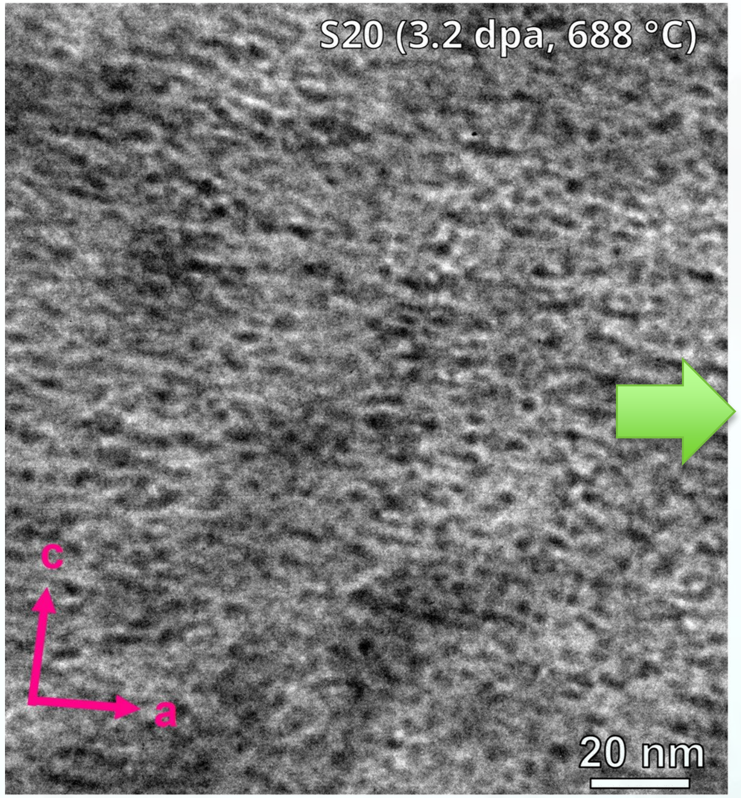
Hypothesis: Rayleigh scattering from radiation-induced voids caused excessive attenuation at high dose and high temperature

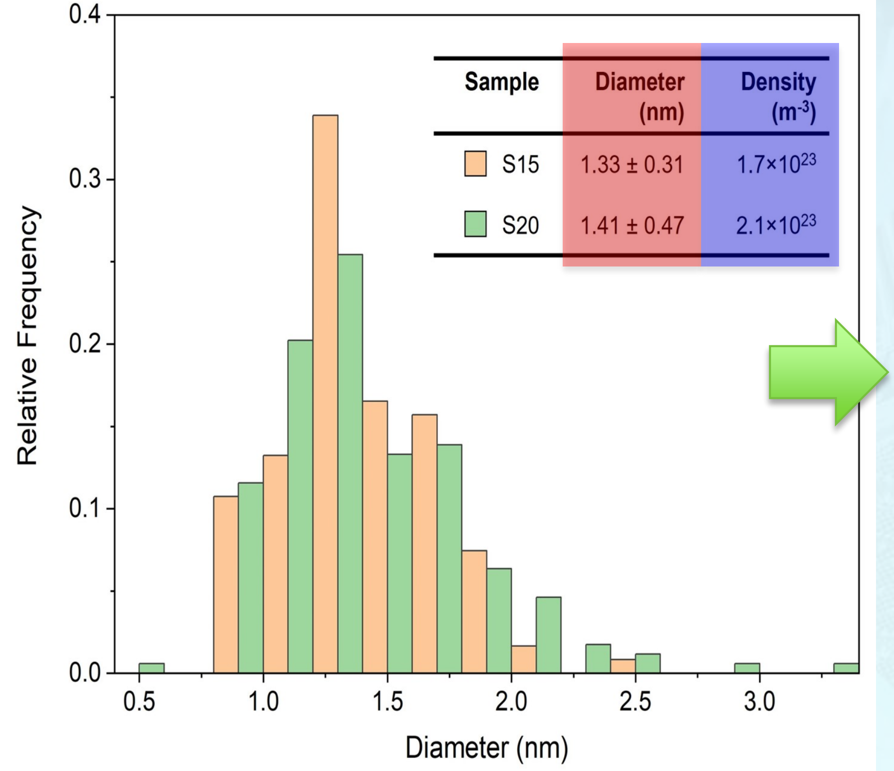




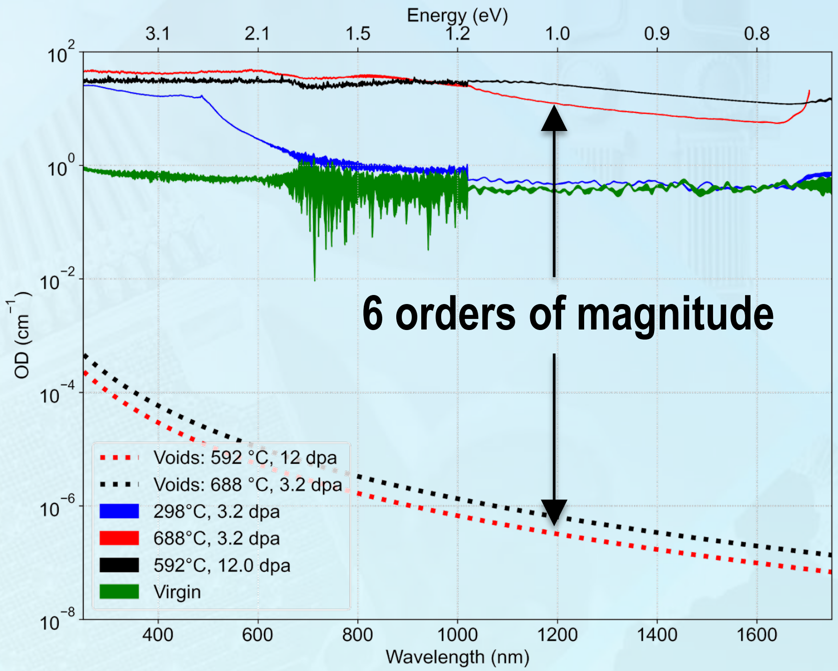
C. Kinoshita and S.J. Zinkle, "Potential and limitations of ceramics in terms of structural and electrical integrity in fusion environments," *Journal of Nuclear Materials* **233–237** (1996) 100–110.

We found voids! But it turns out they can't explain the attenuation…





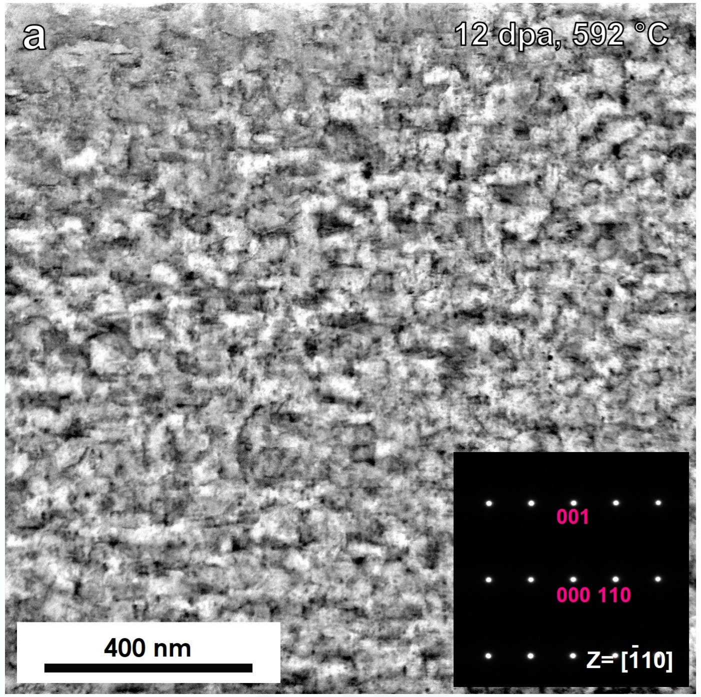
Sample	Diameter (nm)	Density (m^{-3})
S15	1.33 ± 0.31	1.7×10^{23}
S20	1.41 ± 0.47	2.1×10^{23}

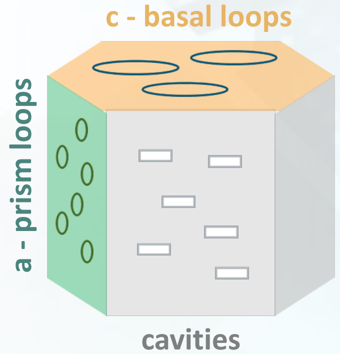


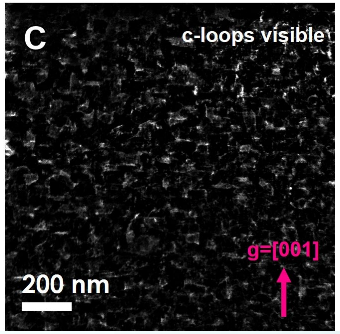
$$\sigma_{voids} = \frac{8\pi}{3}\left(\frac{2\pi n_{med}}{\lambda}\right)^4 r_{voids}^6 \left(\frac{m^2-1}{m^2+2}\right)^2$$

$$OD_{voids} = \frac{N_{voids}\sigma_{voids}}{\ln(10)}$$

We were wrong, but only because we picked the wrong microstructural feature (dislocation loops)!



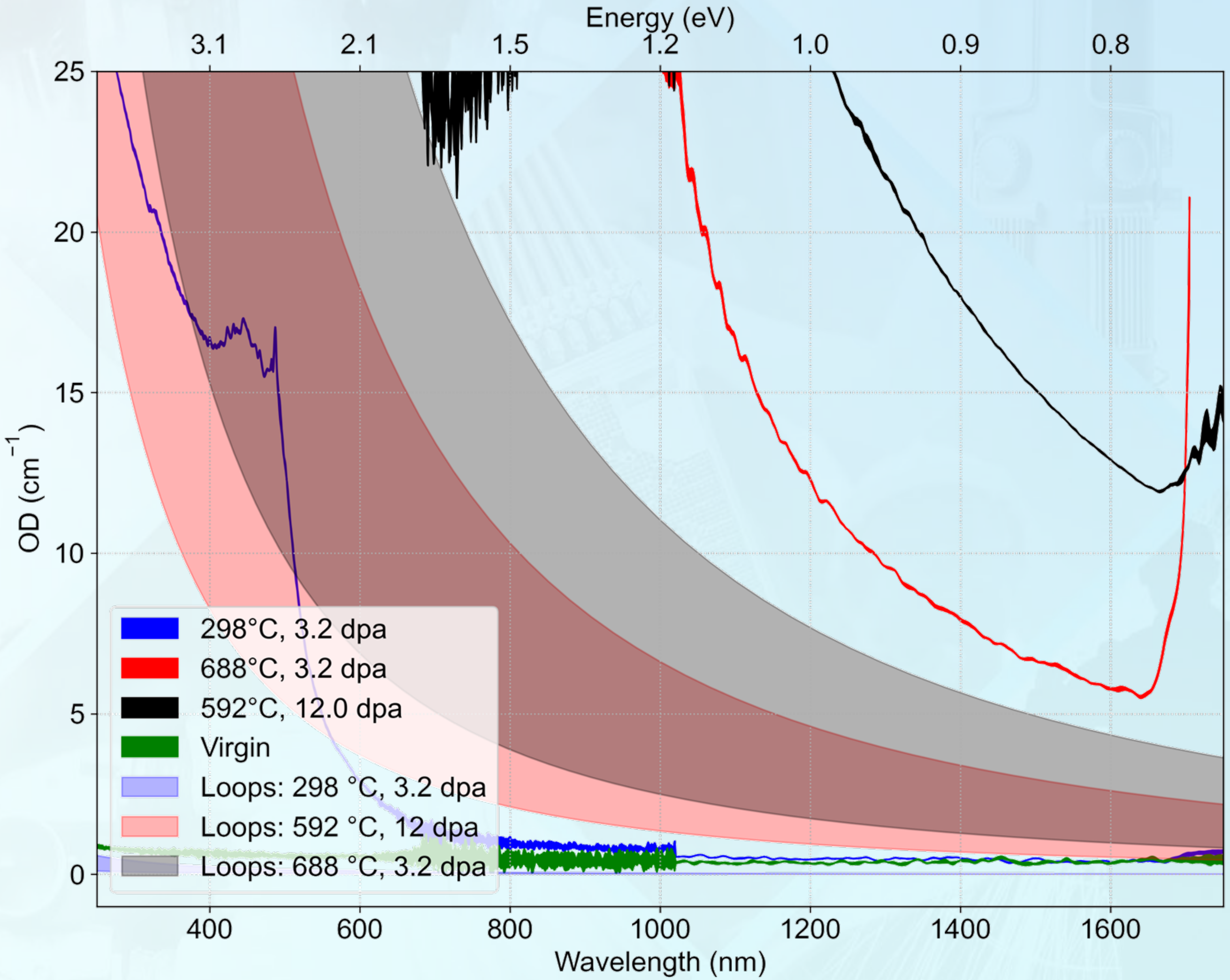




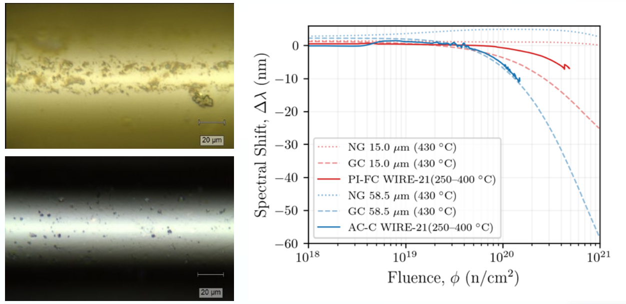
Temp. (°C)	Dose (dpa)	Dislocation density (m^{-2})	c-loop diameter (nm)	c-loop density (m^{-3})
298	3.2	0	7.2±1.6	2.1×10^{22}
592	12	3.14×10^{14}	45.3±8.9	2.5×10^{21}
688	3.2	2.80×10^{14}	62.5±11.5	1.2×10^{21}

$$\sigma_{loops} = \frac{8\pi^3 r_{loops}^4}{\lambda^2}\left(\frac{\Delta n}{n_{med}}\right)$$

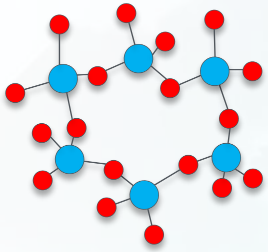
$$OD_{loops} = \frac{N_{loops}\sigma_{loops}}{\ln(10)}$$



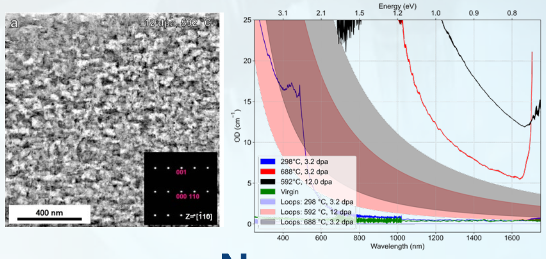
Summary and conclusions



Radiation-induced coating dimensional changes



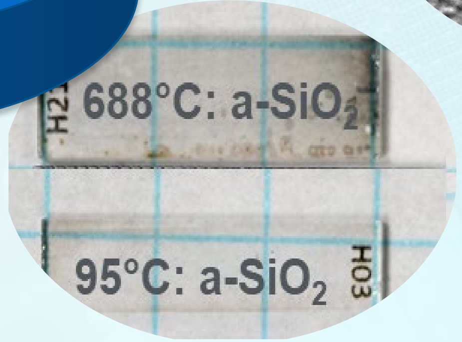
No… Needs more analysis



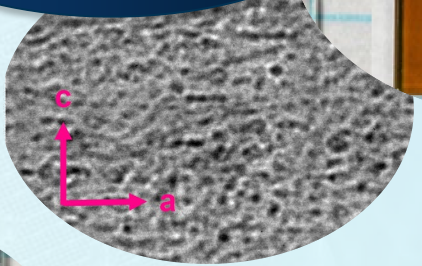
No…

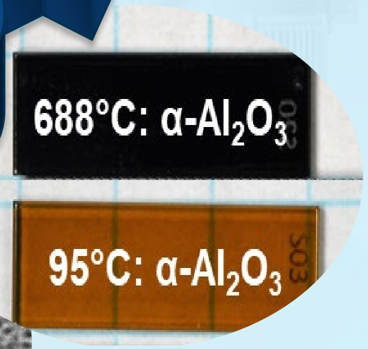
What caused the large drift we see during irradiation?

Do we understand radiation-induced structural changes in SiO_2?



Are sapphire fibers an option in-core at >1,000°C?





Questions?

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