High-Performance Nanostructured Thermoelectric Materials and Generators for In-Pile Power Harvesting

Advanced Sensors and Instrumentation Annual Webinar

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Project Overview

Objectives:

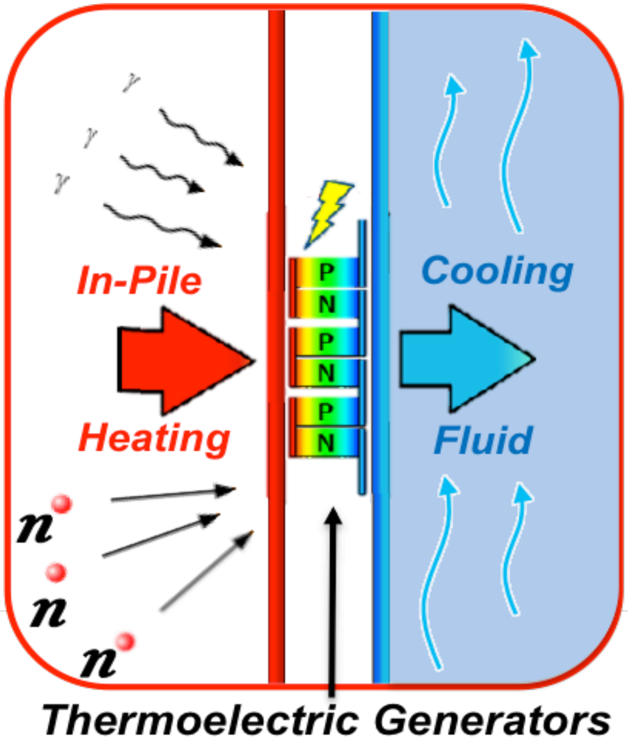
- Investigate the in-pile performance of high-efficiency nanostructured bulk thermoelectric materials and devices
- Develop radiation-resistant thermoelectric materials and devices for in-pile power harvesting

Participants:

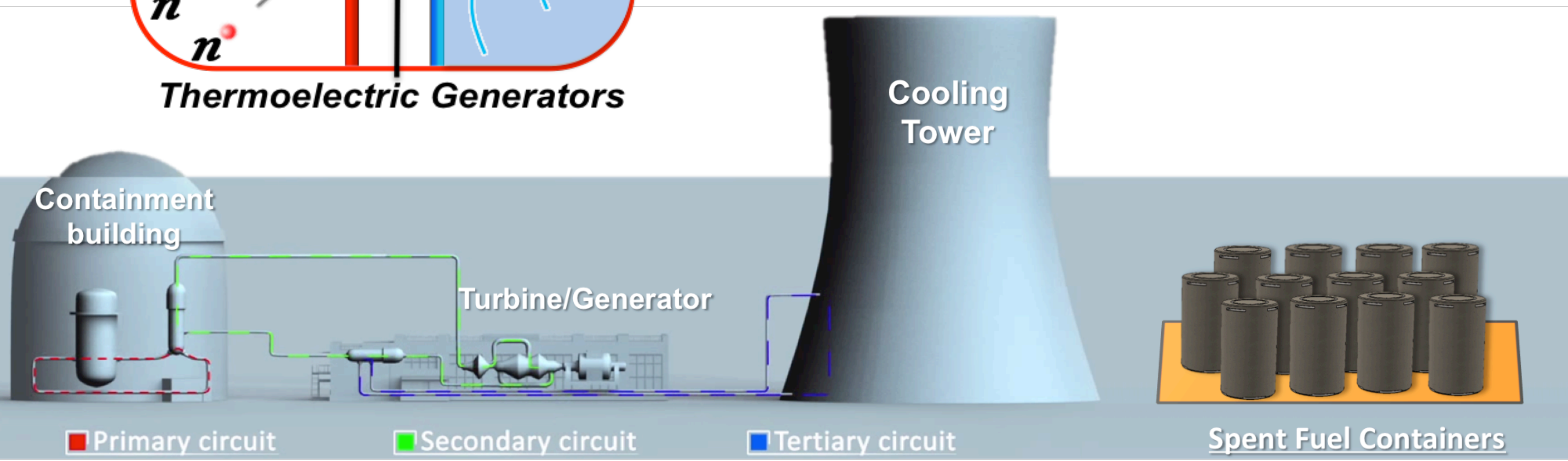
- Yanliang Zhang, University of Notre Dame;
- Mercouri Kanatzidis, Northwestern University;
- Josh Daw, Idaho National Laboratory.

Schedule: 10/2018 - 09/2021

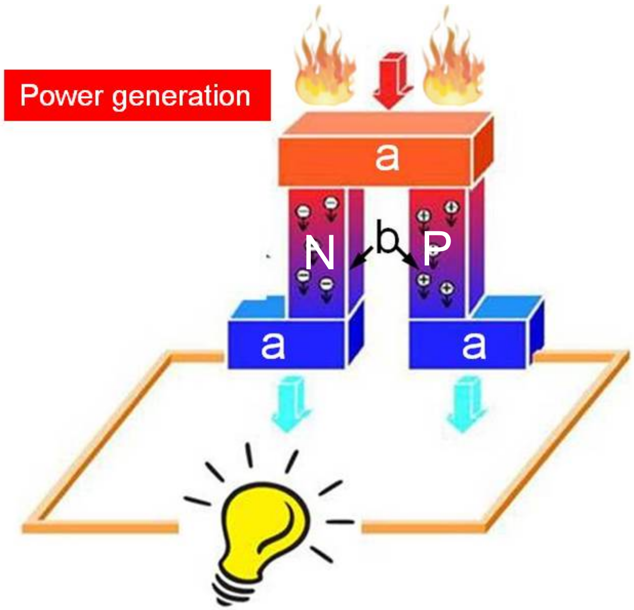
Nanostructured Bulk Thermoelectric Generators for In-pile Power Harvesting



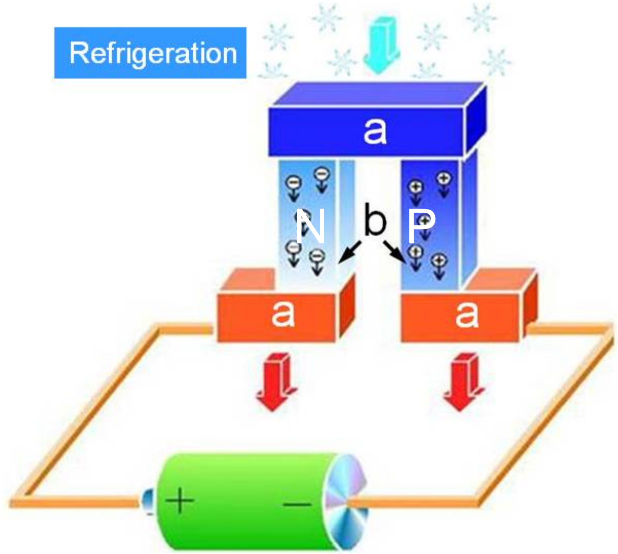
- Thermal energy is very abundant in nuclear power plants;
- The nanostructured bulk thermoelectric materials have significantly higher efficiency and potentially improved radiation resistances over bulk materials.



Principles of Thermoelectric (TE) Energy Conversion

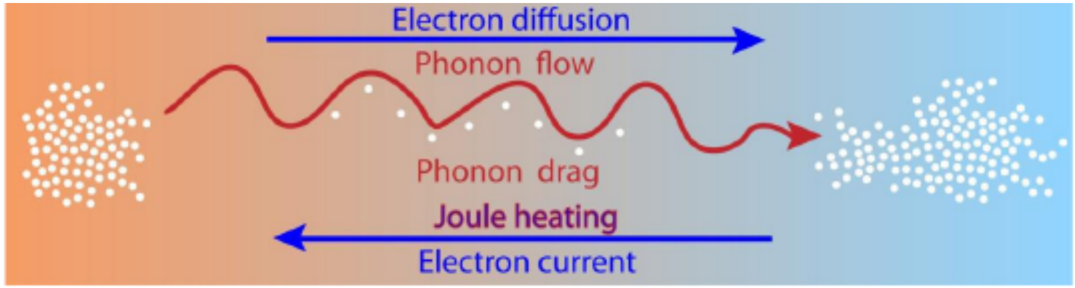


Seebeck effect



Peltier effect

Electrical power generation



Electrons **Phonons**

Energy carriers

Electron flow is the “working fluid” for cooling and power generation.

Nano-Engineering to Increase Thermoelectric Figure of Merit ZT

Seebeck coefficient — Electrical conductivity

$$ZT = \frac{\alpha^2\sigma}{\kappa_E + \kappa_L}T$$

Electronic — Lattice
thermal conductivity

Power factor: $\alpha^2\sigma$

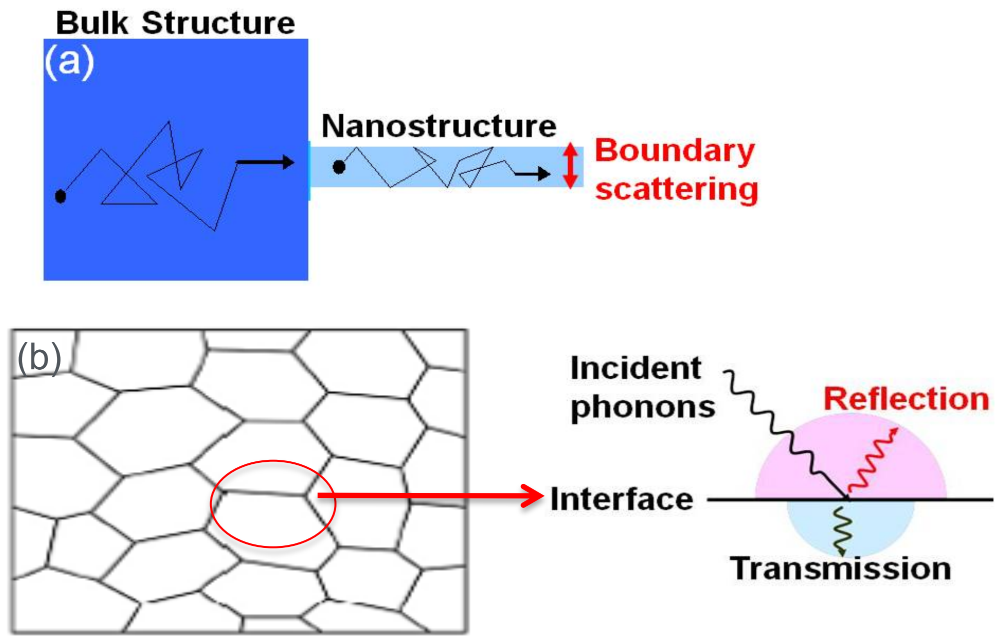
Mean free path

Electrons
1-100 nm

Phonons
1-500 nm

Device efficiency increases with ZT and ΔT

$$\eta_{max} = \frac{T_H - T_C}{T_H}\frac{\sqrt{1+Z\bar{T}}-1}{\sqrt{1+Z\bar{T}}+\frac{T_C}{T_H}}$$



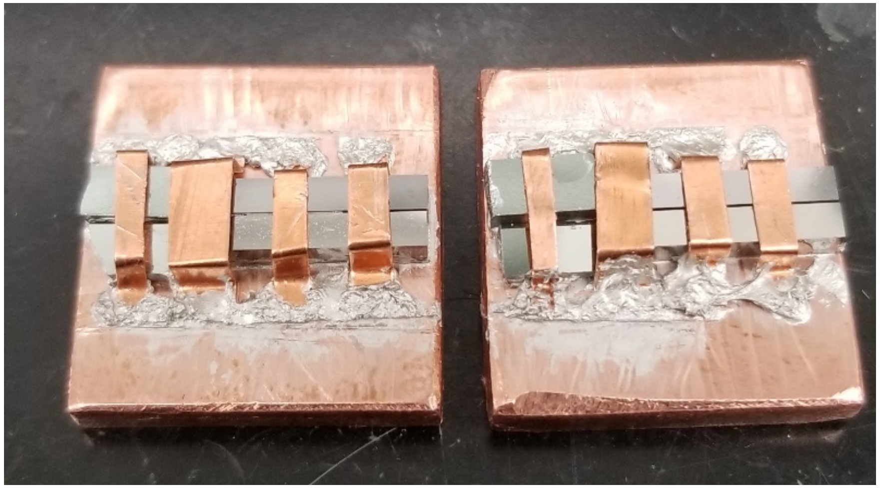
Summary of accomplishments

- Performed post irradiation examination on ion-irradiated thermoelectric materials
- Prepared thermoelectric generators (TEGs) and associated instrumentation for in-pile irradiation and in-situ testing
- Initiated in-situ measurement of TEG performances in the core of MIT reactor

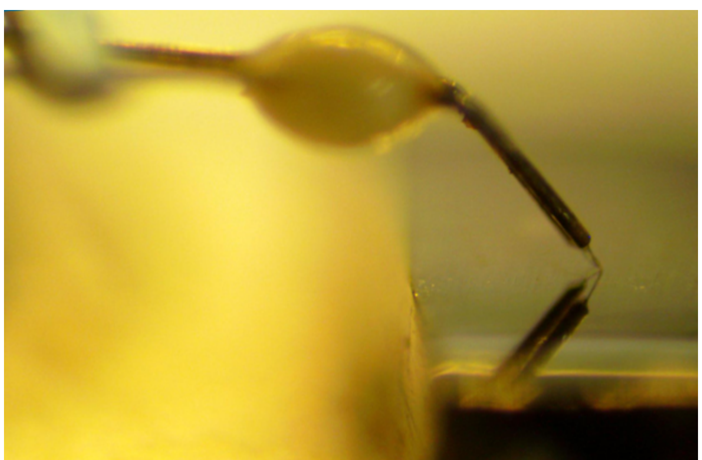
Technology Impact

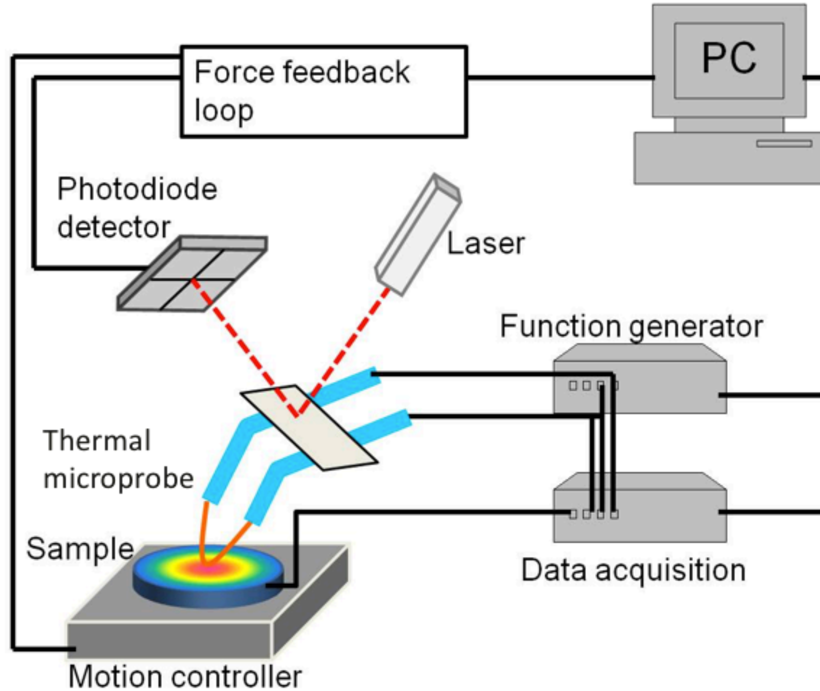
- Generate power in the nuclear reactor core or other NPP areas
- Enable TEG-powered sensors for in-pile instrumentation
- Enable self-powered wireless sensors for broad NPP applications
- Improve the safety of nuclear power plants
- Reduce the cost of sensors installation and maintenance

Ion-irradiation effect on thermoelectric properties



Half-Heusler and PbTe thermoelectric materials prepared for ion irradiation

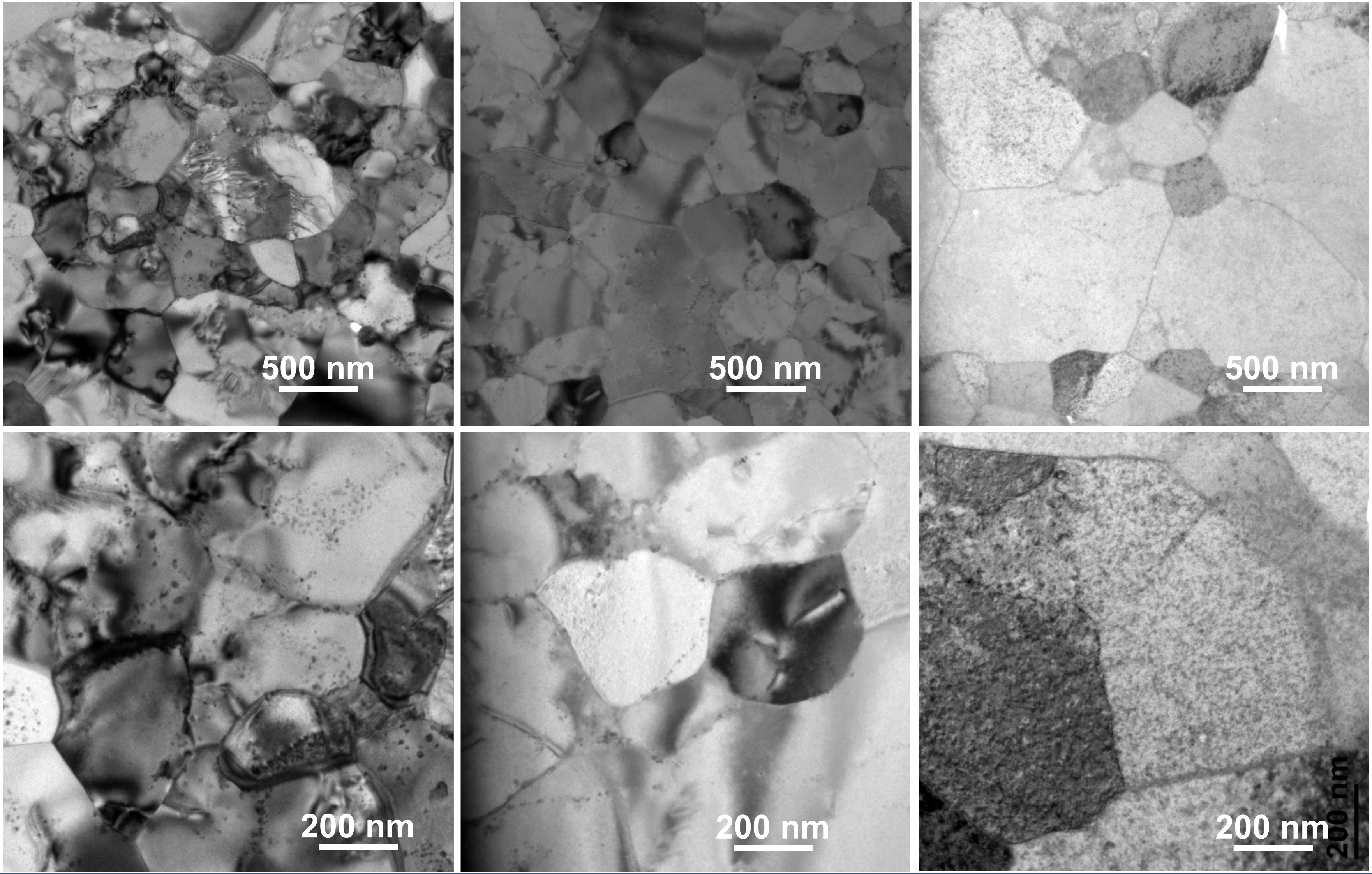




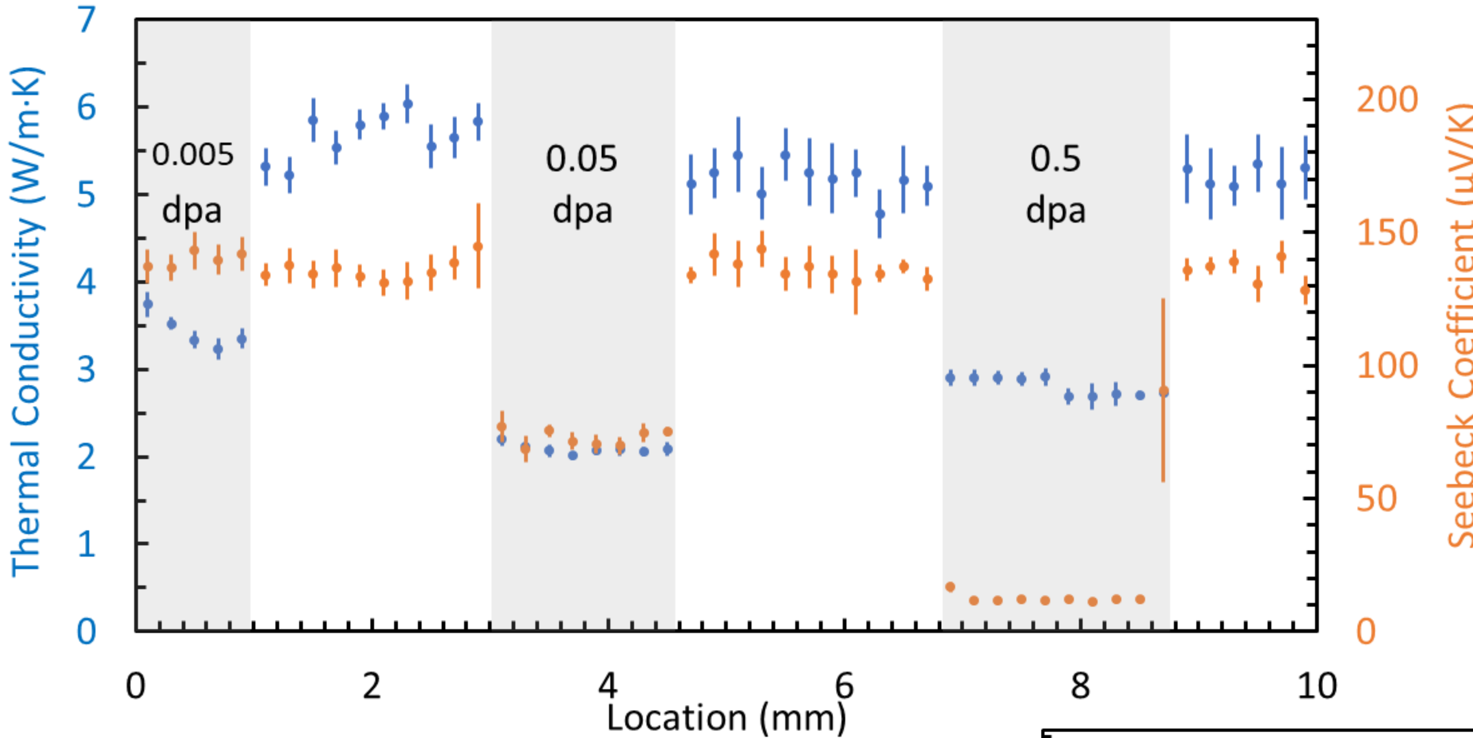
Scanning thermal probe to map thermal conductivity and Seebeck coefficient simultaneously

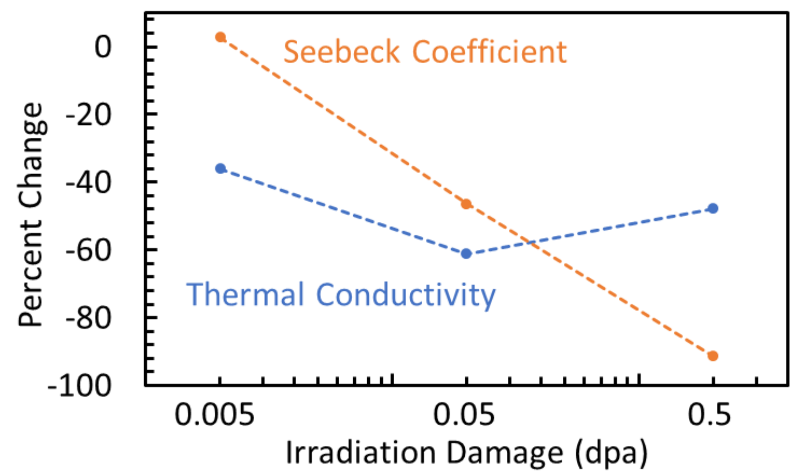
Microstructures of ion-irradiated half Heusler materials

Un-irradiated | **0.05 dpa** | **0.5 dpa**



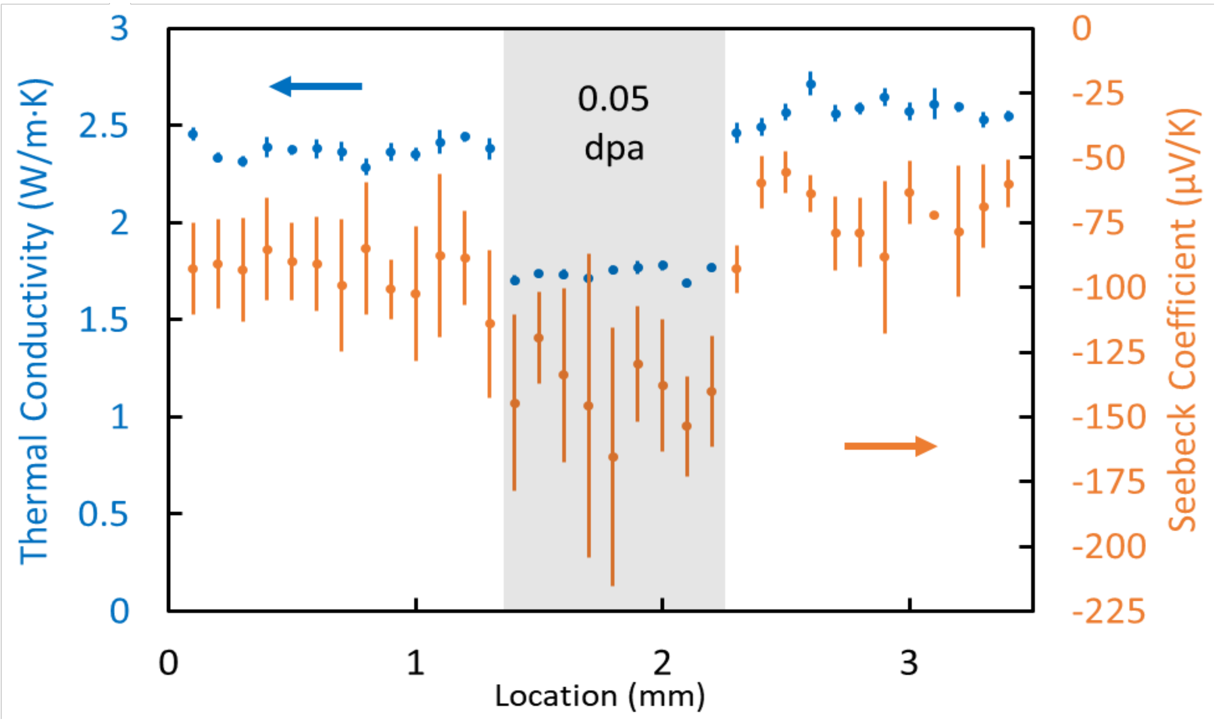
Thermoelectric property change due to ion irradiation





Reduced thermal conductivity and Seebeck coefficient due to ion irradiation

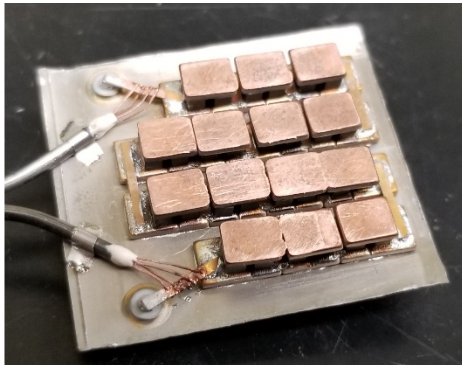
Thermoelectric property of ion irradiated PbTe material

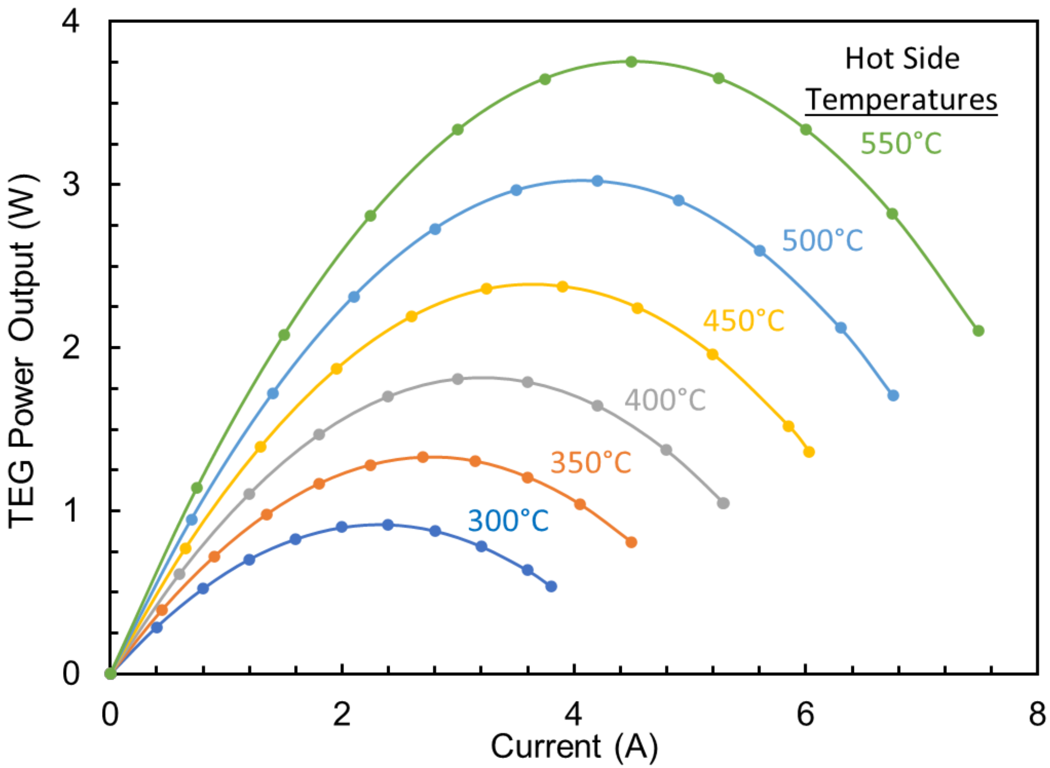


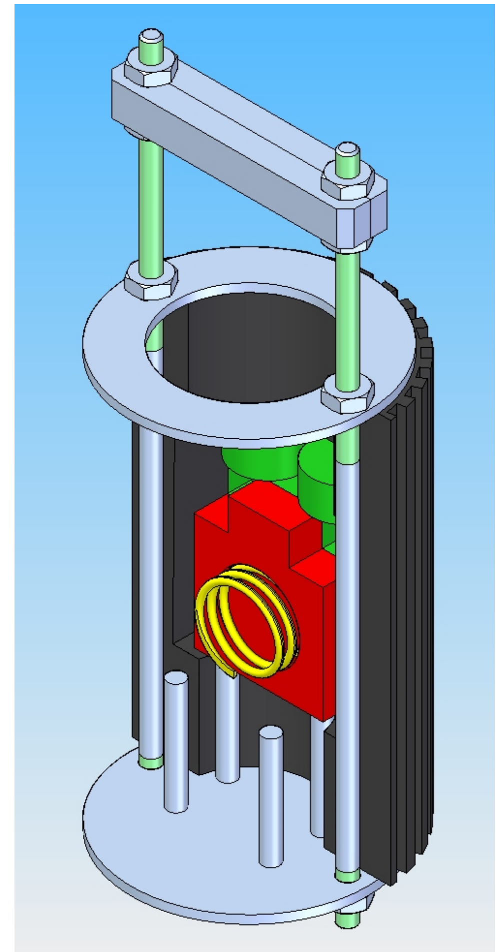
Percent Change	
Thermal Conductivity	-30%
Seebeck Coefficient	+71%

Reduced thermal conductivity and increased Seebeck coefficient due to ion irradiation

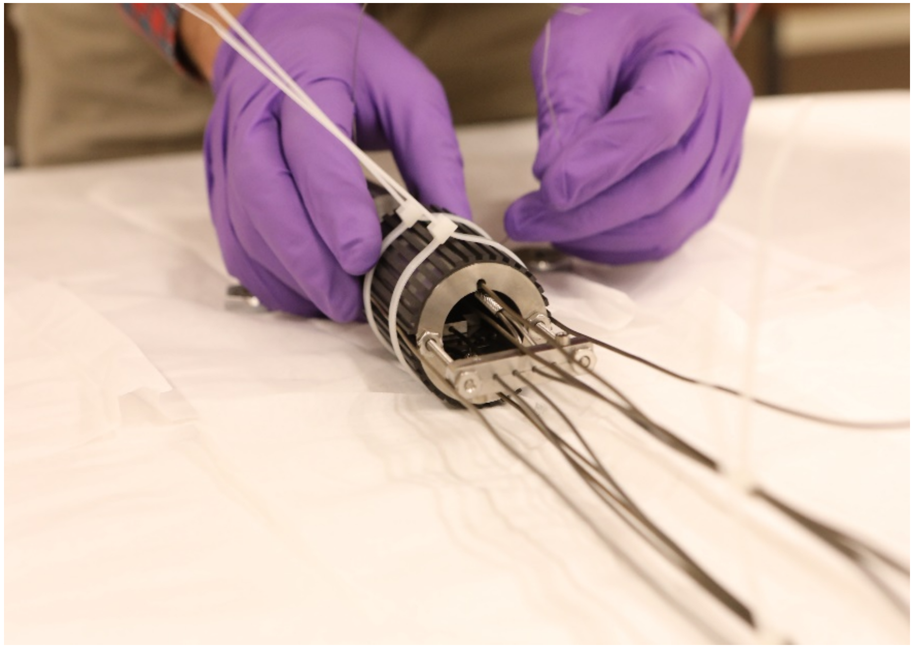
Thermoelectric generators (TEGs) for in-pile testing



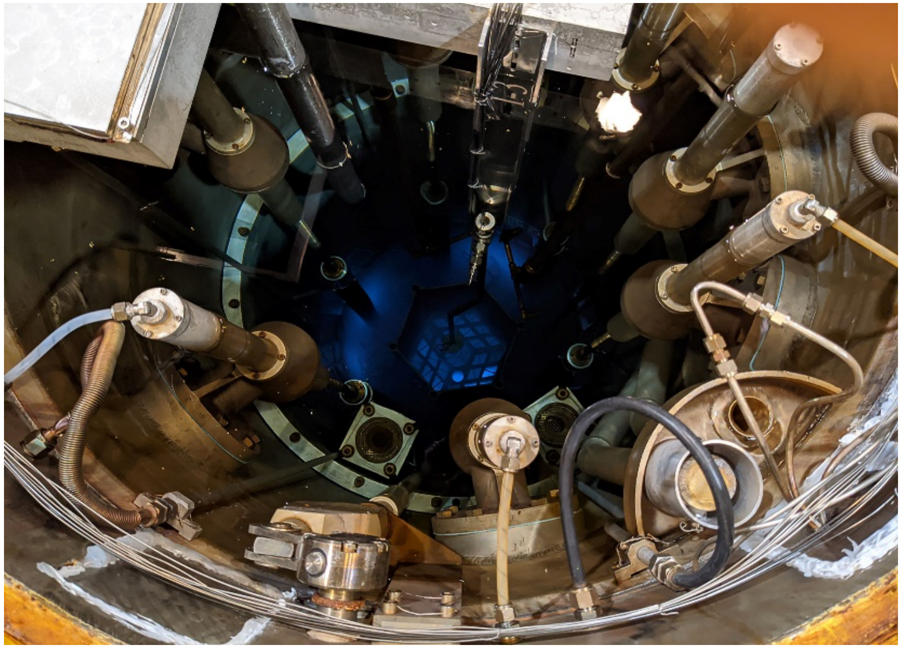




Two TEGs inserted into the core of MIT reactor

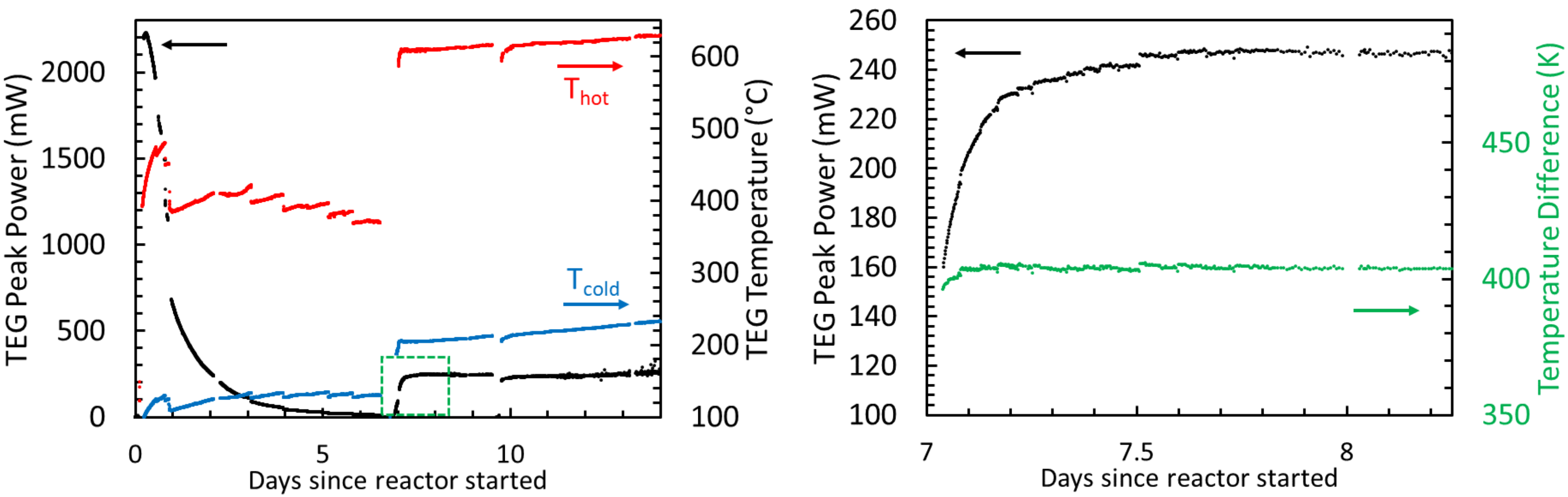


TEGs assembled with the capsule



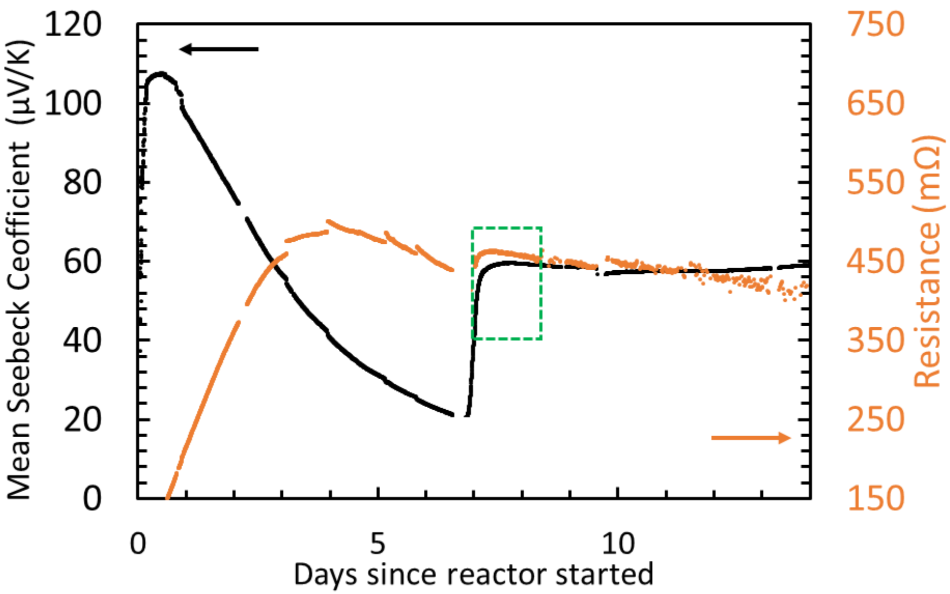
TEG capsule inserted into reactor core

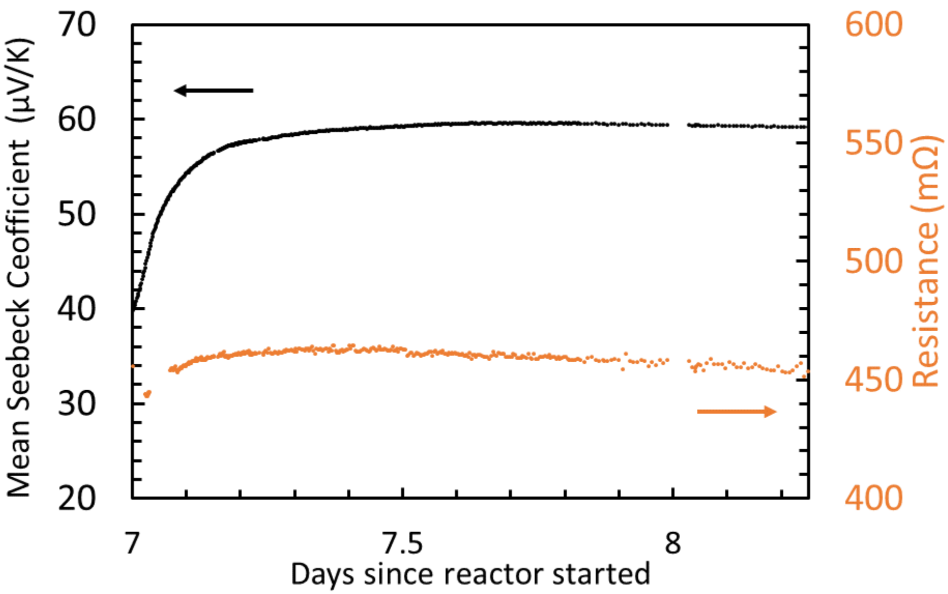
In-situ TEG in-core testing results



- A sharp initiative decrease of TEG power output due to **irradiation damage** when TEG is operating at relatively low temperature
- A significant increase of TEG power output due to **in-situ healing** when TEG is operating at increased temperature

In-situ healing of radiation damage





In-situ healing of radiation damage evidenced by the increased Seebeck coefficient and reduced resistivity

Conclusion

- Ion irradiation can result in significant change in materials microstructure and thermoelectric properties
- In-core neutron irradiation can cause significant damage and diminish the TEG power output
- In-situ healing of radiation damage occurs when TEG is operating in core at elevated temperature
- The TEG can operate in core and produce steady >40 mW/cm^2 power density, sufficient to power a wide range of sensors
- The TEG can enable self-powered wireless sensors for both in-core and out-of-core nuclear energy applications
- The TEG powered sensors can improve the reliability and reduce the cost of sensors and instrumentation

Acknowledgements

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Collaborators:

- Josh Daw, Idaho National Laboratory
- Mercouri Kanatzidis, Northwestern University
- David Carpenter, MIT