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

Advanced Sensors and Instrumentation

Optical Sensors for Impurity Measurement in Liquid Metal-cooled Fast Reactors

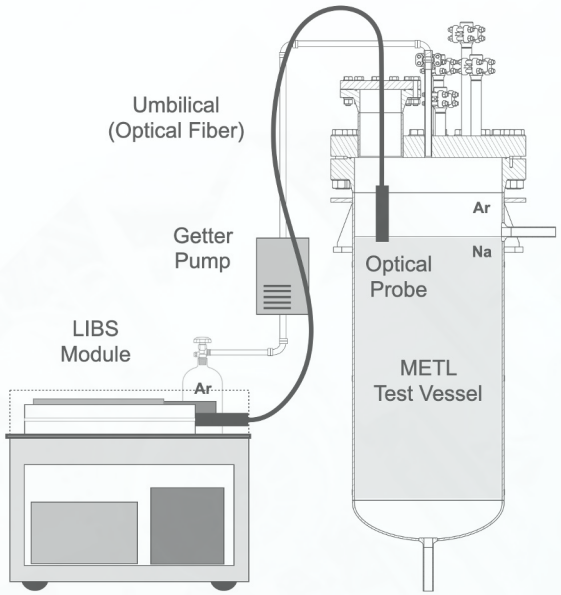
MICHIGAN ENGINEERING
NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

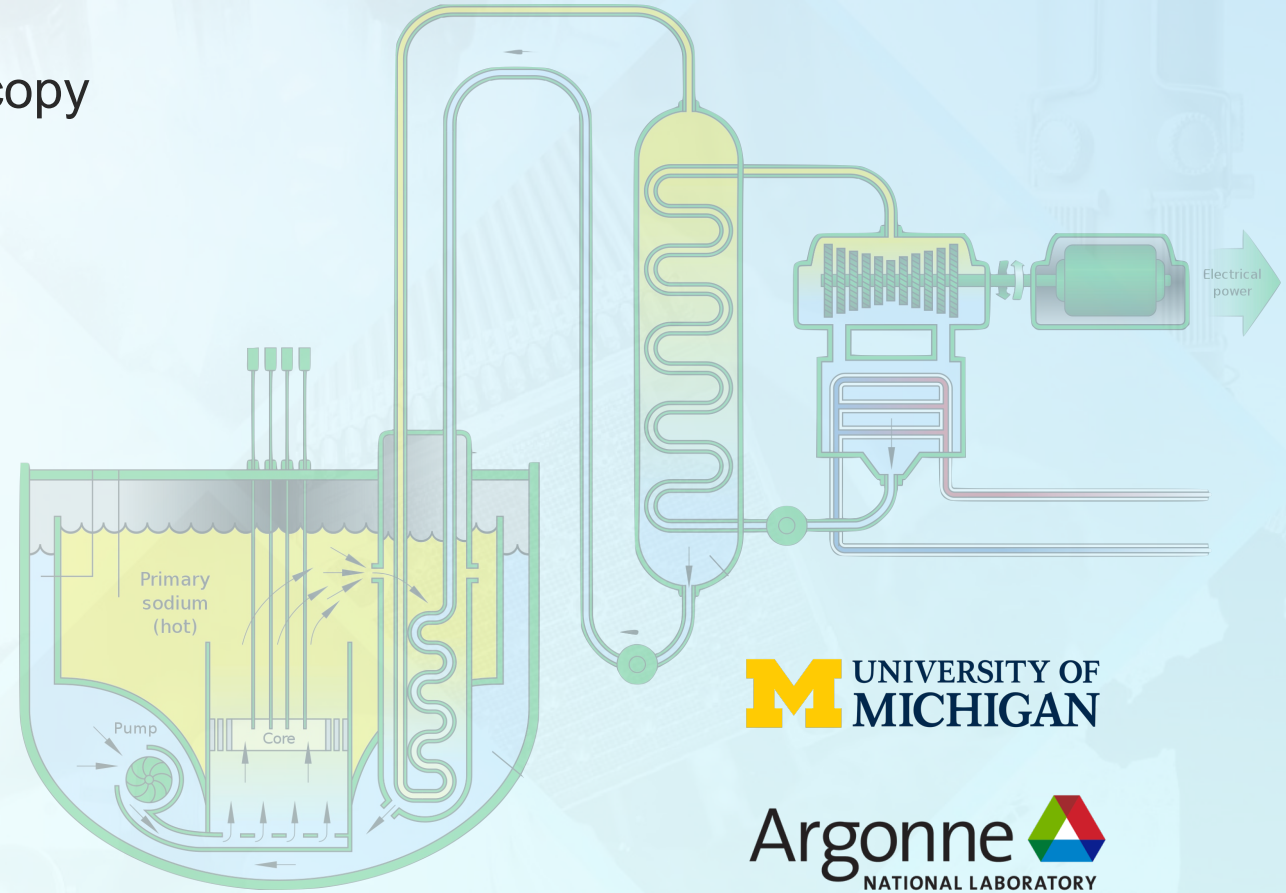
Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
November 4, 6-7, 2024

PI: Milos Burger, Associate Research Scientist
University of Michigan

Project Overview – Coolant impurity detection at METL

- Current technology: Plugging meter at ANL
- Alternative technology: Laser-based spectroscopy
- Progress report – FY2024
- Plans – FY2025





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Argonne NATIONAL LABORATORY

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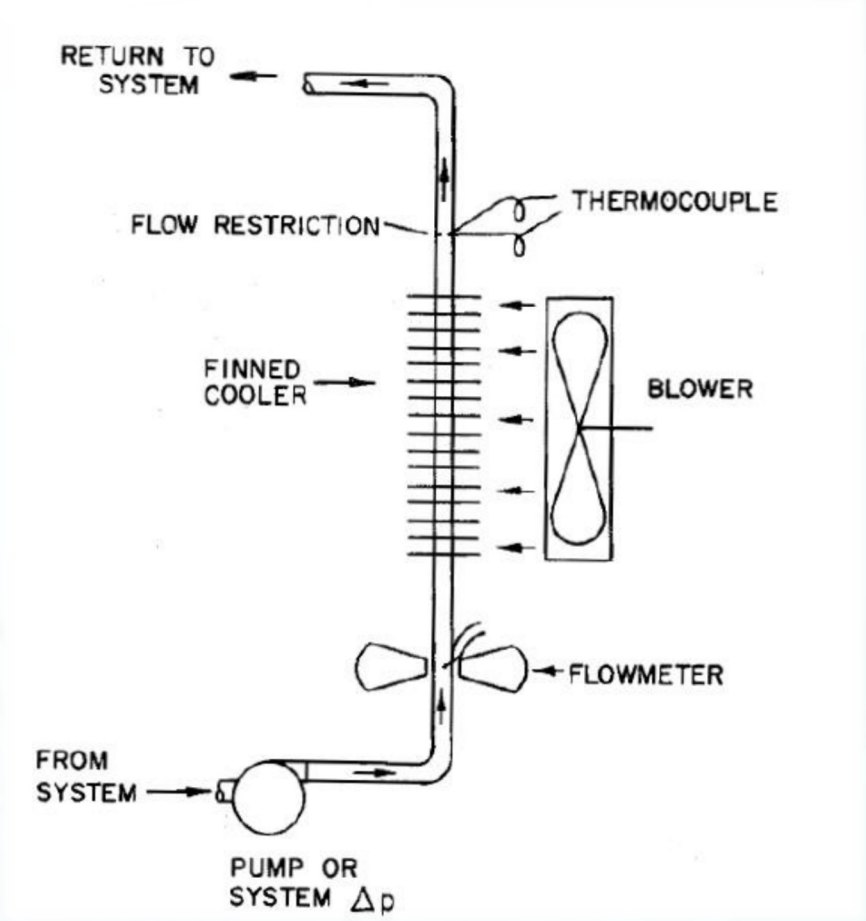
Plugging meter at METL

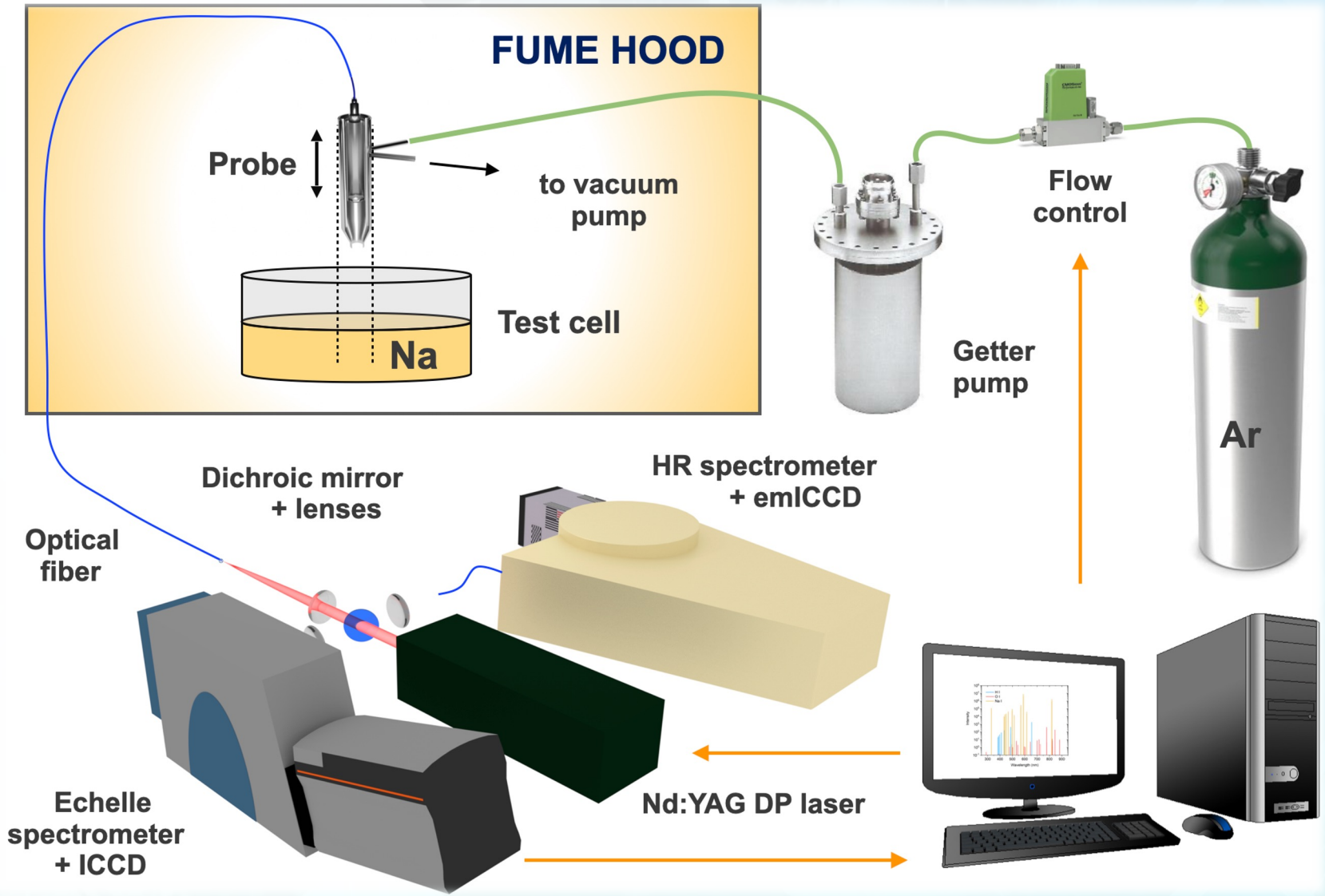


Limitations:

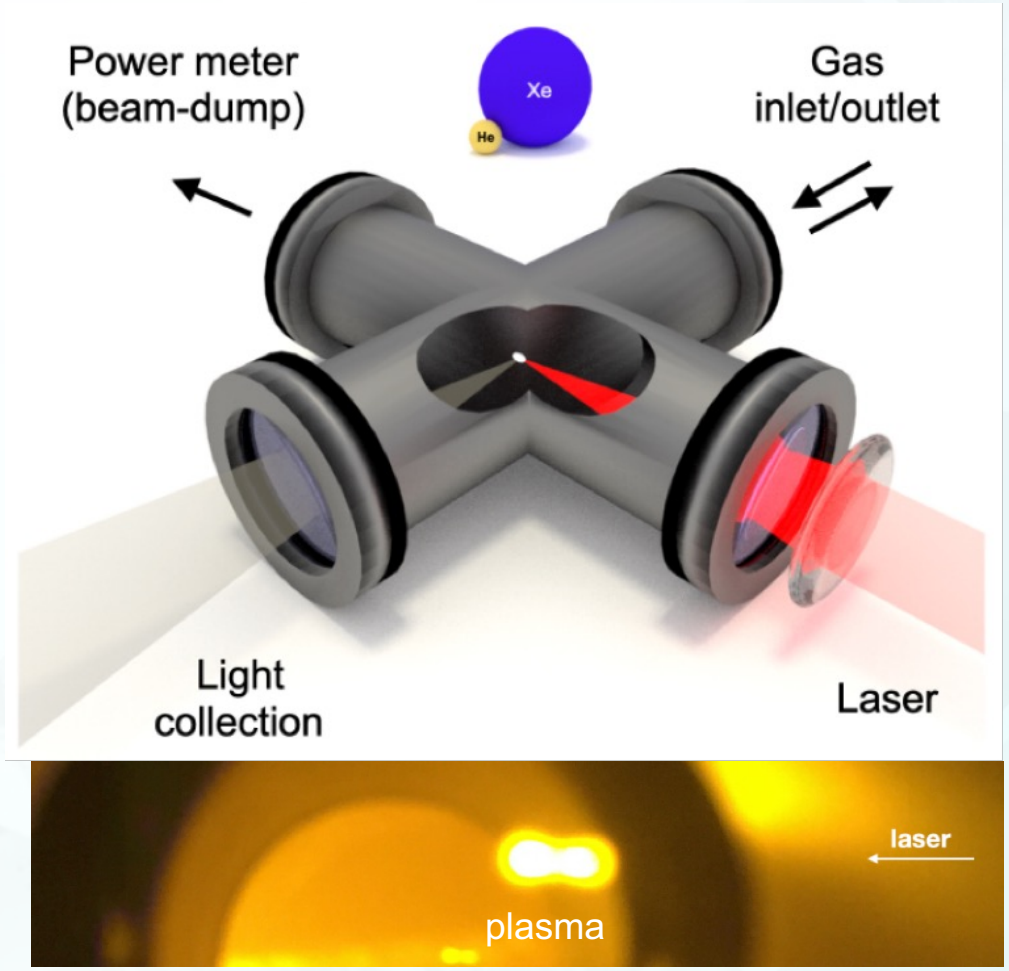
- Non-discriminant measurement technique
- Min ~1h to obtain a measurement result
- Indirect measurement (empirical correlation)

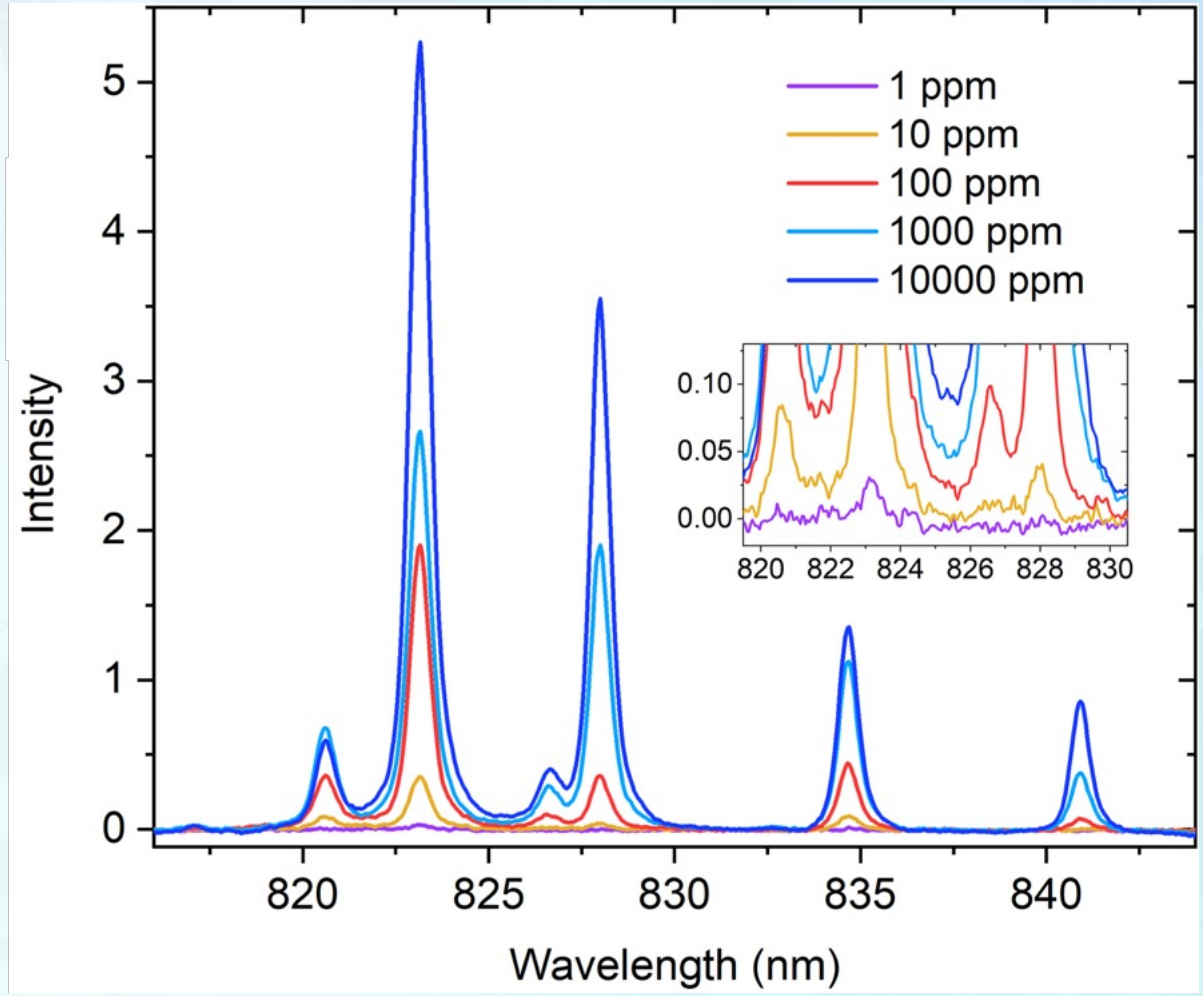
Mechanisms Engineering Test Loop – Phase I Status Report – FY2018

Alternative Approach: Laser-based Sensing



Previous Work: Trace Xe Detection in He





Burger et al. (2021) JAAS

Participants

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Dr. Milos Burger
Dr. Adam Burak
Prof. Igor Jovanovic

Misael Ortiz – MS student
Ethan Zagotta – Senior undergraduate
Joseph Brown – Senior undergraduate
Leandro Frigerio – Ph.D. student

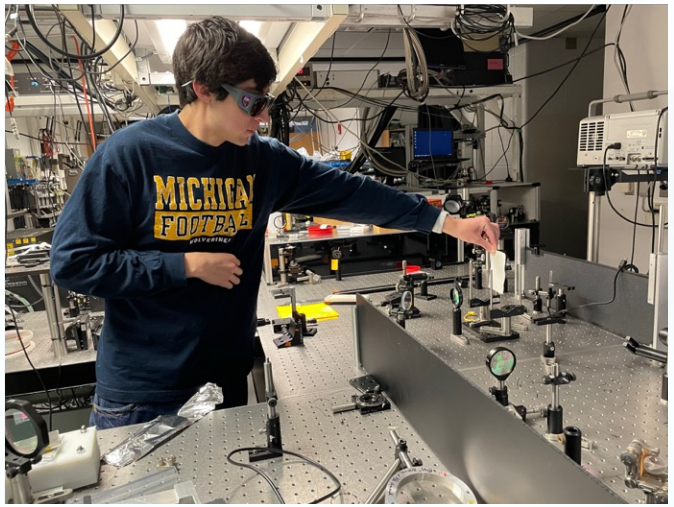
Argonne NATIONAL LABORATORY

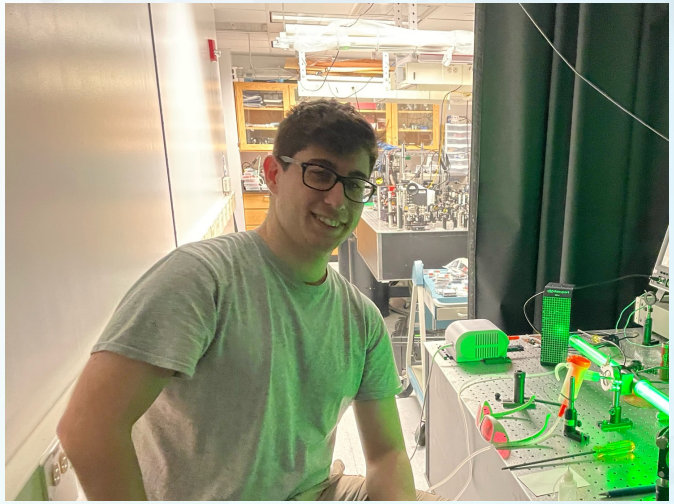
Mr. Edward Kent

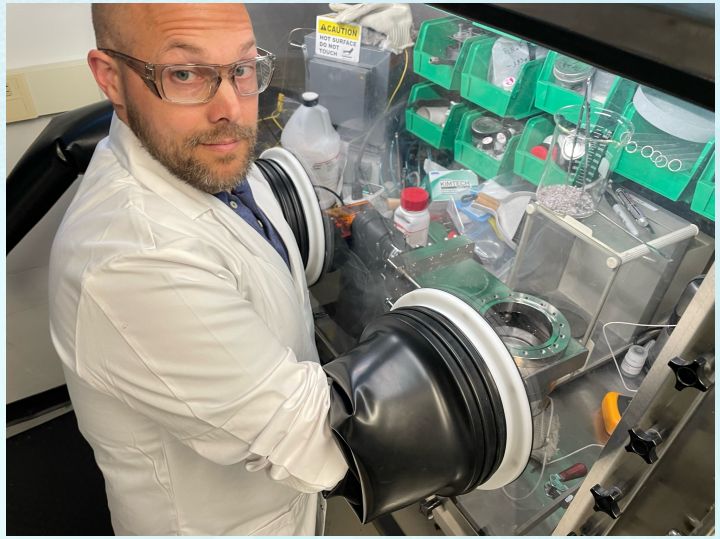
ERCo ENERGY RESEARCH COMPANY

Dr. Robert De Saro
Dr. Joseph Craparo

Participants





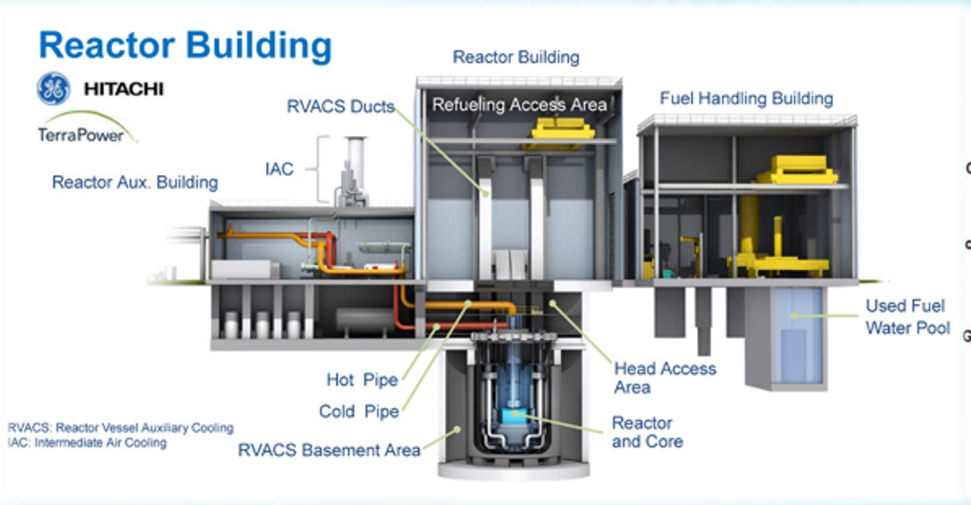


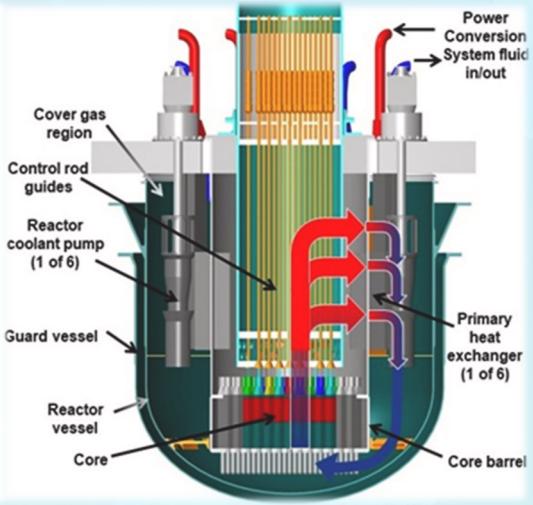
Schedule

Milestone No. / Title	Status	Start Date	Finish Date	% Complete
"M3NU-23-MI-UM__-020101-102 Procured optics, test material, cover gasses, laser upgrades and maintenance"	Complete	10/1/23	6/30/24	100%
"M3NU-23-MI-UM__-020101-103 Constructed and validated experimental testbed"	Complete	10/1/23	6/30/24	100%
"M3NU-23-MI-UM__-020101-105 Measured LOD for trace impurities in liquid Na at operationally relevant temperatures"	On Schedule	4/1/24	3/31/25	45%

Technology Impact

- The technology will be tested at the Mechanisms Engineering Test Loop (METL) facility at the Argonne National Laboratory
- Target capabilities: 24/7 operation, high sensitivity/specificity, instantaneous results, compact size
- Relevance in the nuclear energy industry for reactor designs that employ metal-based cooling





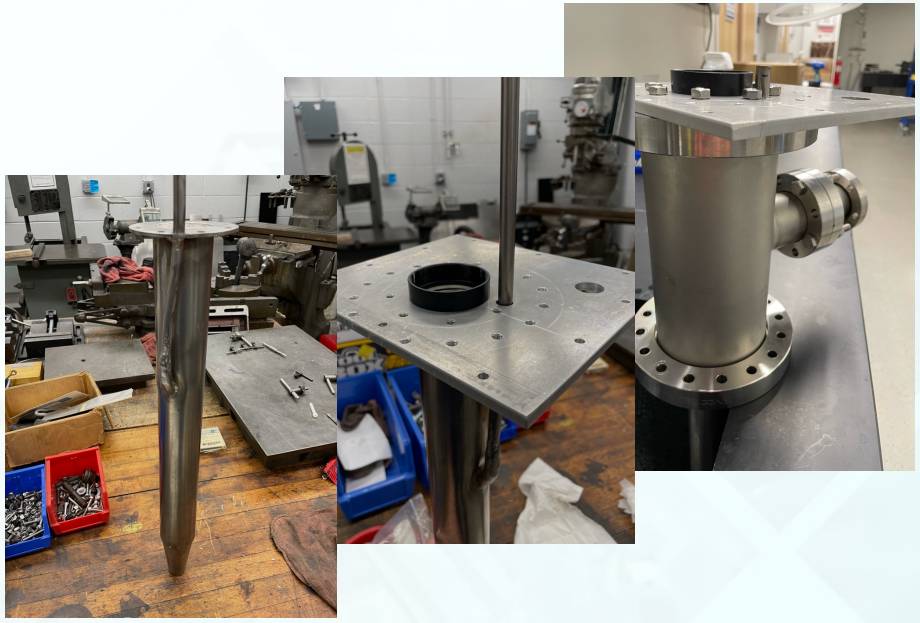
Argonne NATIONAL LABORATORY

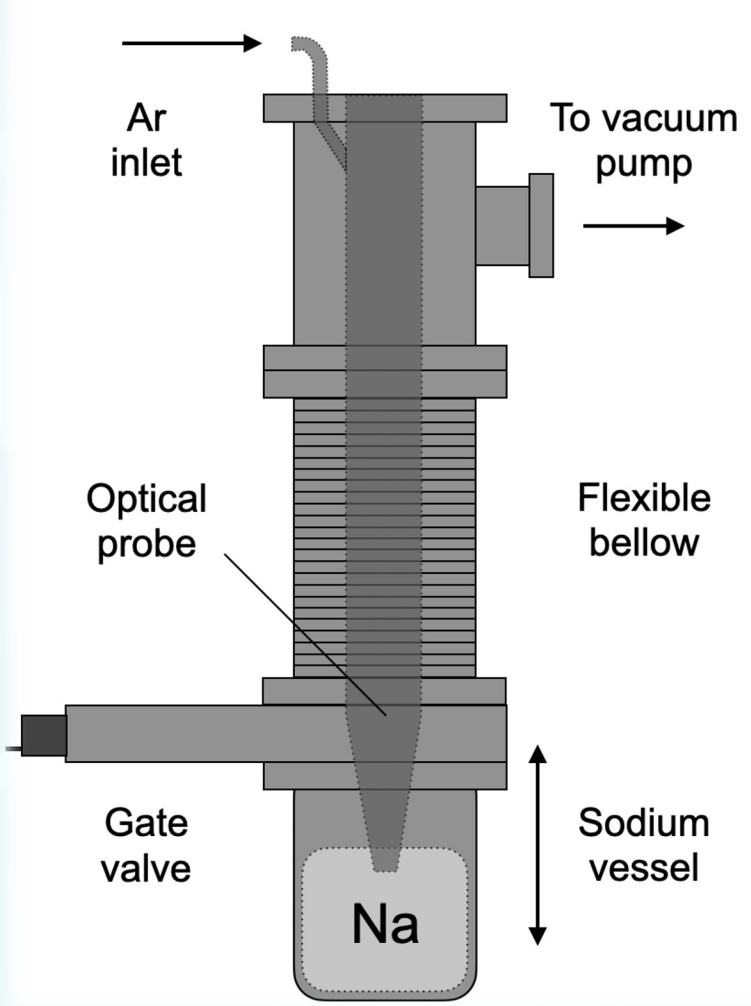
TerraPower

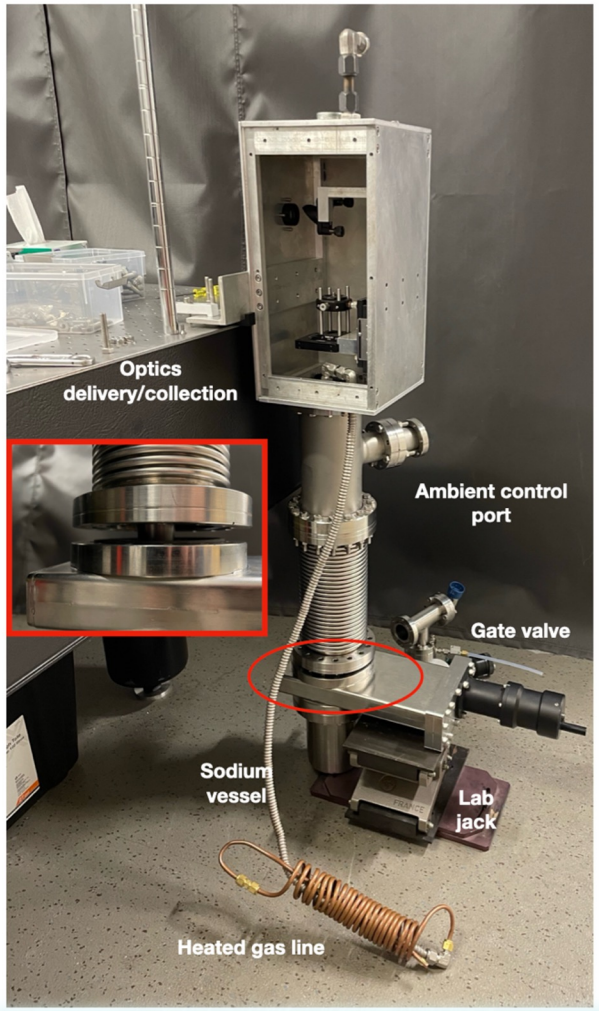
Westinghouse

Laboratory Testbed

- Custom-built system supports laser delivery, sample probing, and plasma emission collection
- Stainless steel immersible probe
- ConFlat fittings enable high vacuum
- Detachable Na vessel

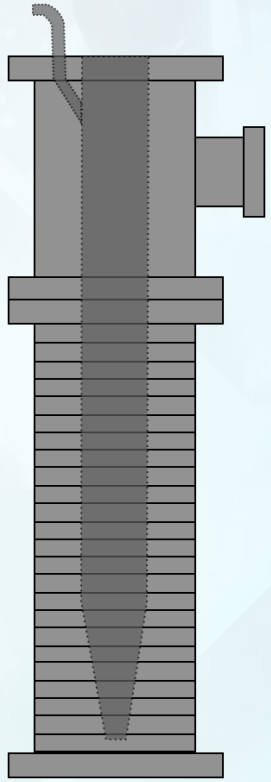


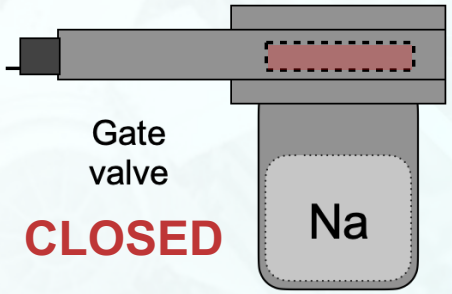




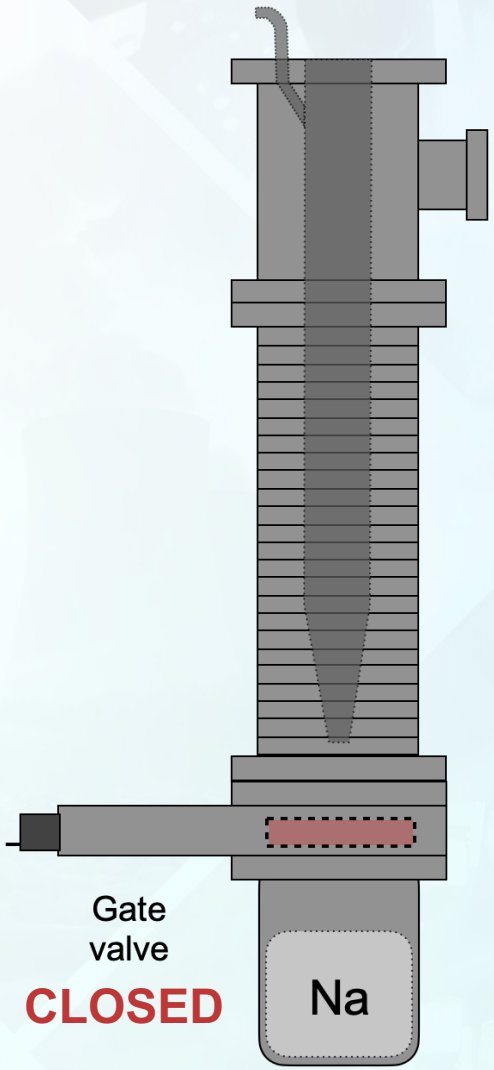
Laboratory Testbed: Operation Principle

Sample preparation
(glovebox)





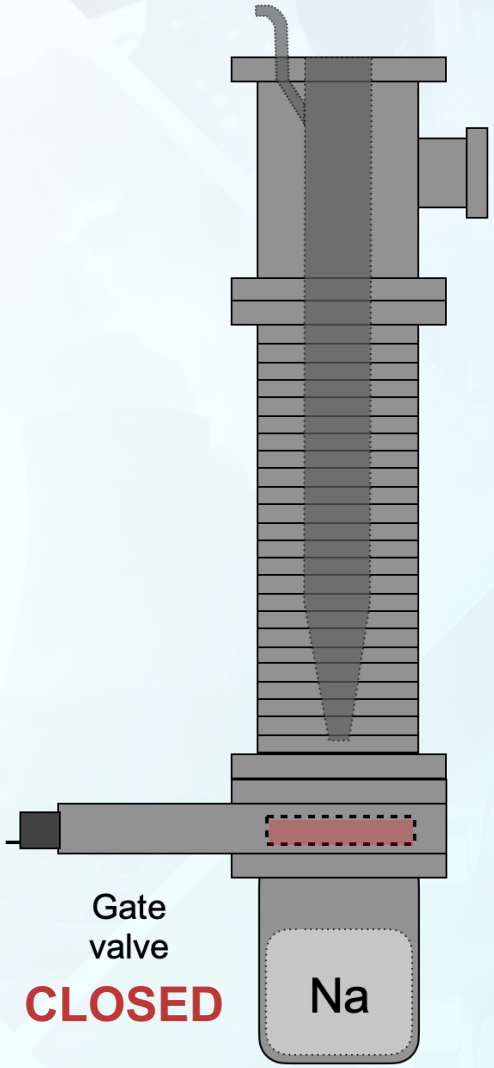
Laboratory Testbed: Operation Principle



Air evacuation
(turbo pump)

Na heating
(band heater)

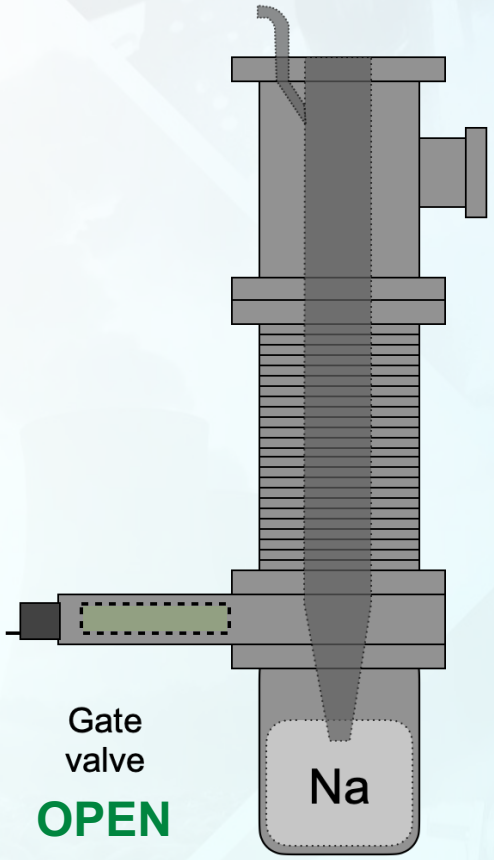
Laboratory Testbed: Operation Principle



Ar (1 bar)

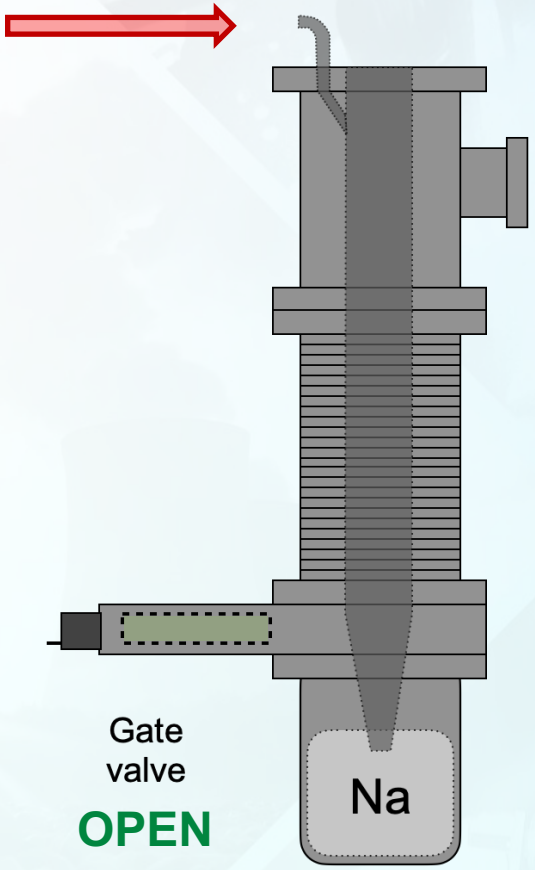
Na heating
(band heater)

Laboratory Testbed: Operation Principle



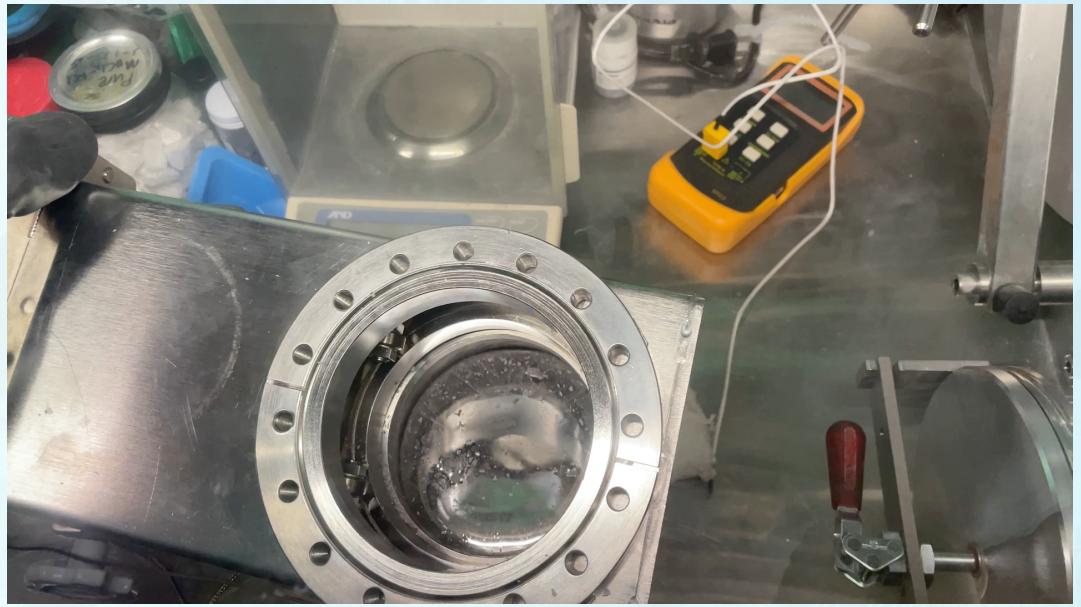
Laboratory Testbed: Operation Principle

Heated Ar

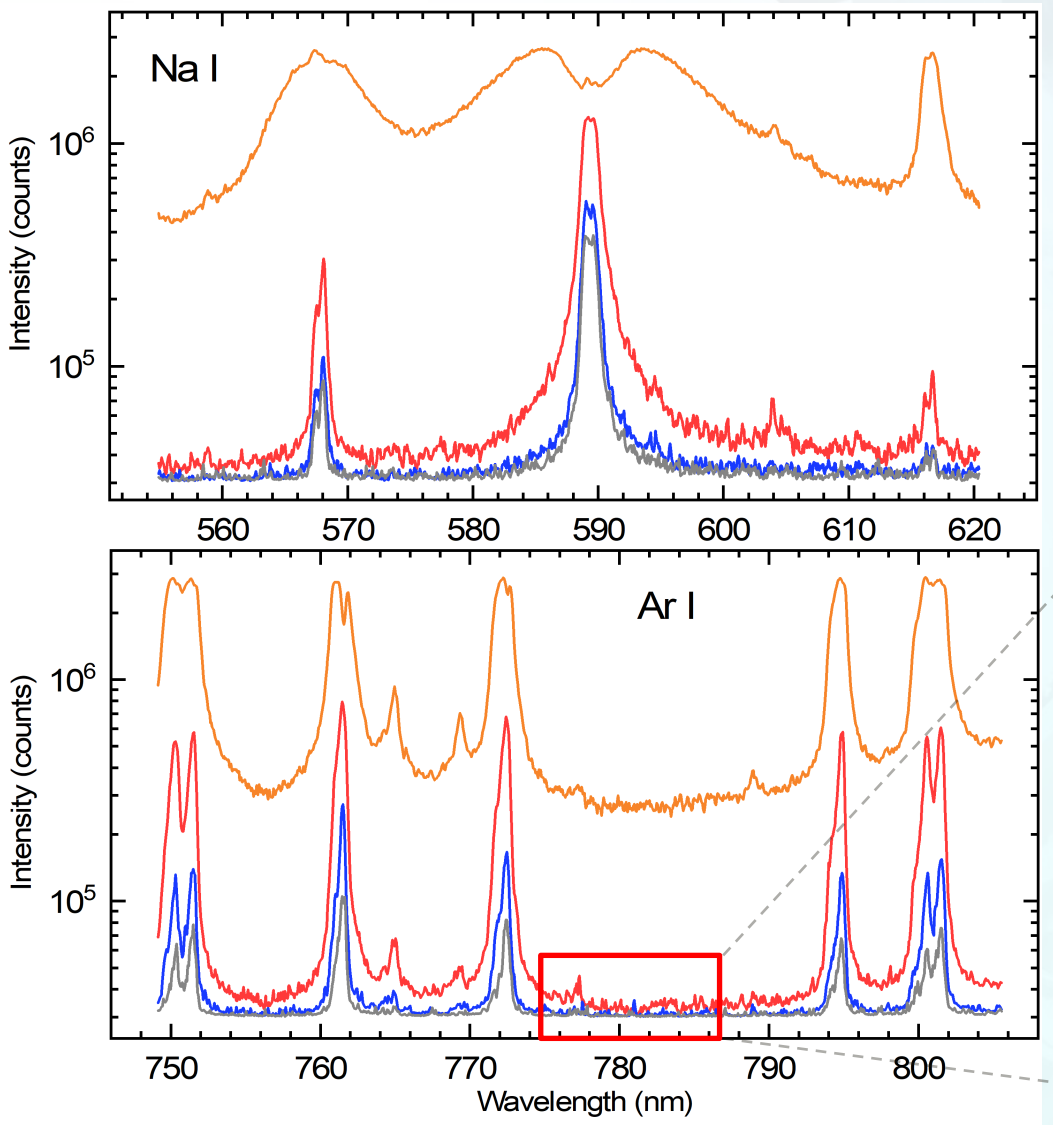


Sample Preparation

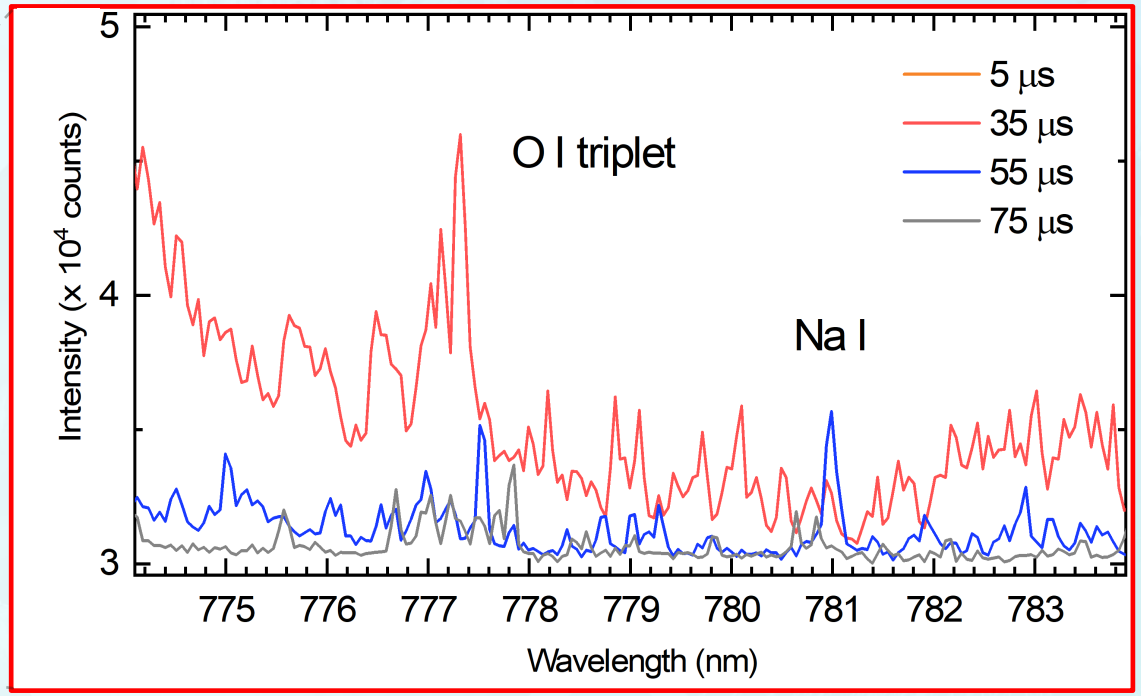
- Testbed features a sample vessel that can hold 1 kg of sodium
- Test sample was not high purity and is commercially available (99.8% purity)
- The gate valve and its O-ring limits the maximum operating temperature to 250 °C when the gate valve is open



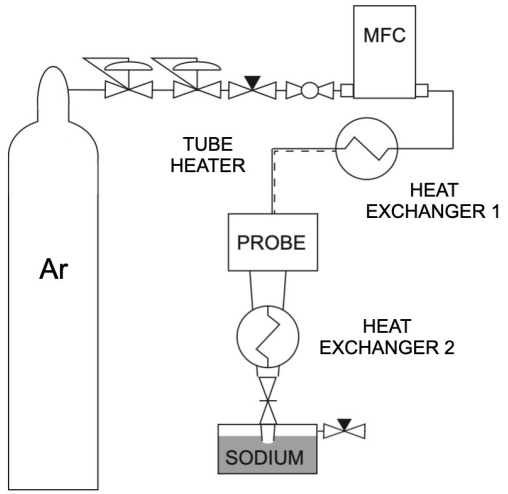
Characteristic Spectral Signatures

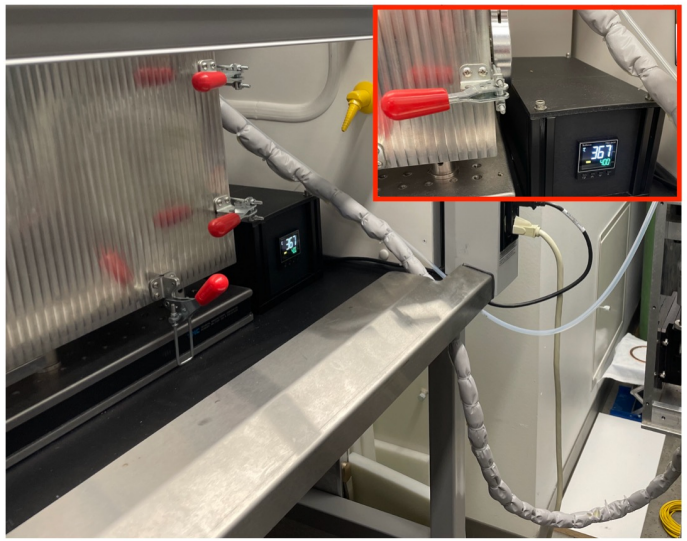


- Sodium doublet self-reversed at early delays
- Closer examination of the seemingly steady spectral region shows an oxygen triplet consisting of O I (777.19 / 777.42 / 777.53) nm and atomic line of sodium (Na I 780.98 nm)



Challenges during FY24

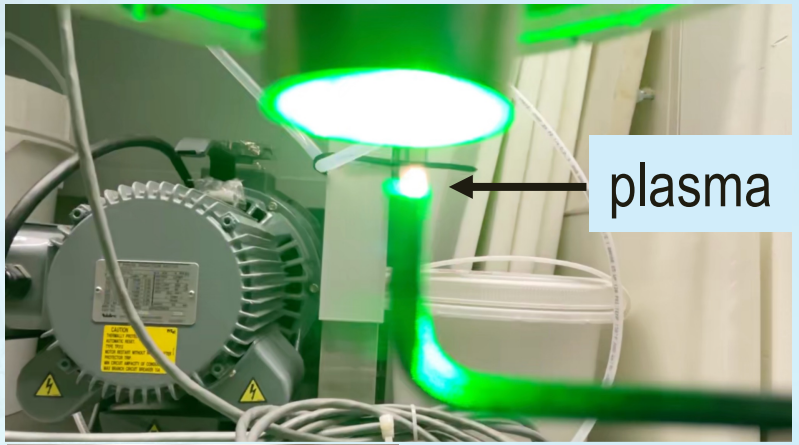


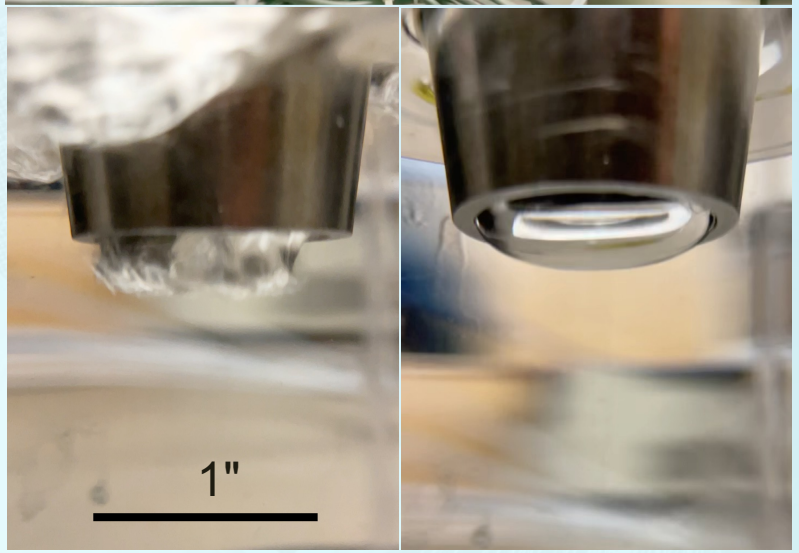


- Lens-to-sample distance
- Probe heating
- Recording parameters
- Flow rate optimization
- Gas/sodium temperature

Property	Water		Sodium	
	Solid	Liquid	Solid	Liquid
Density (kg/m^3)	920	997	951	927
Latent heat of evaporation (kJ/mol)	40.5		107.0	
Heat capacity (J/(mol K)	37.6	75.2	28.4	32.3
Melting point (K)	273.2		371.1	
Liquid range (K)	100		794	
Isothermal compressibility (10^{-10} N^{-1} m^2)	2	4.9	1.7	1.9
Surface tension(mJ/ m^2)	...	72	...	190
Viscosity (Poise=0.1kg/(m s))	...	0.01	...	0.007
Thermal conductivity (J/(m s K))	2.1	0.58	134	84

F. Franks, "Water, A Matrix of Life", 2nd Ed. (2000).



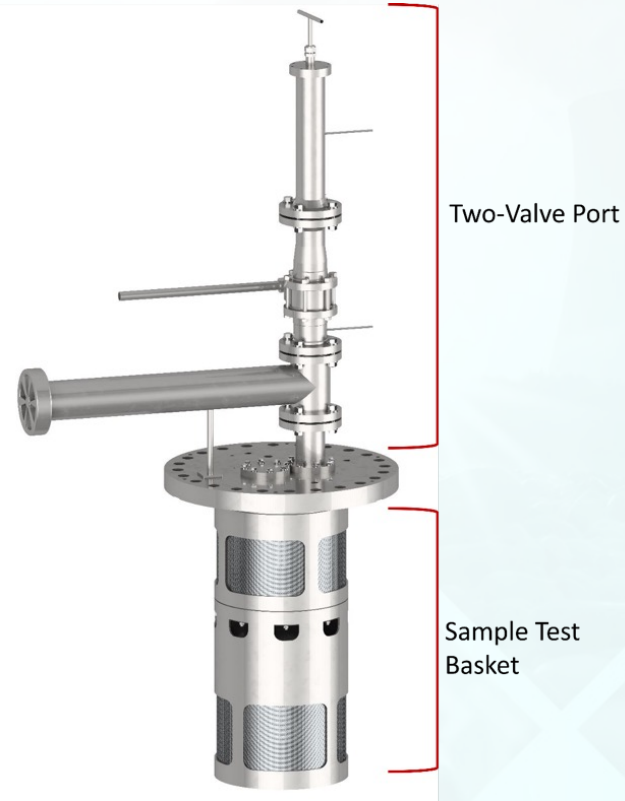


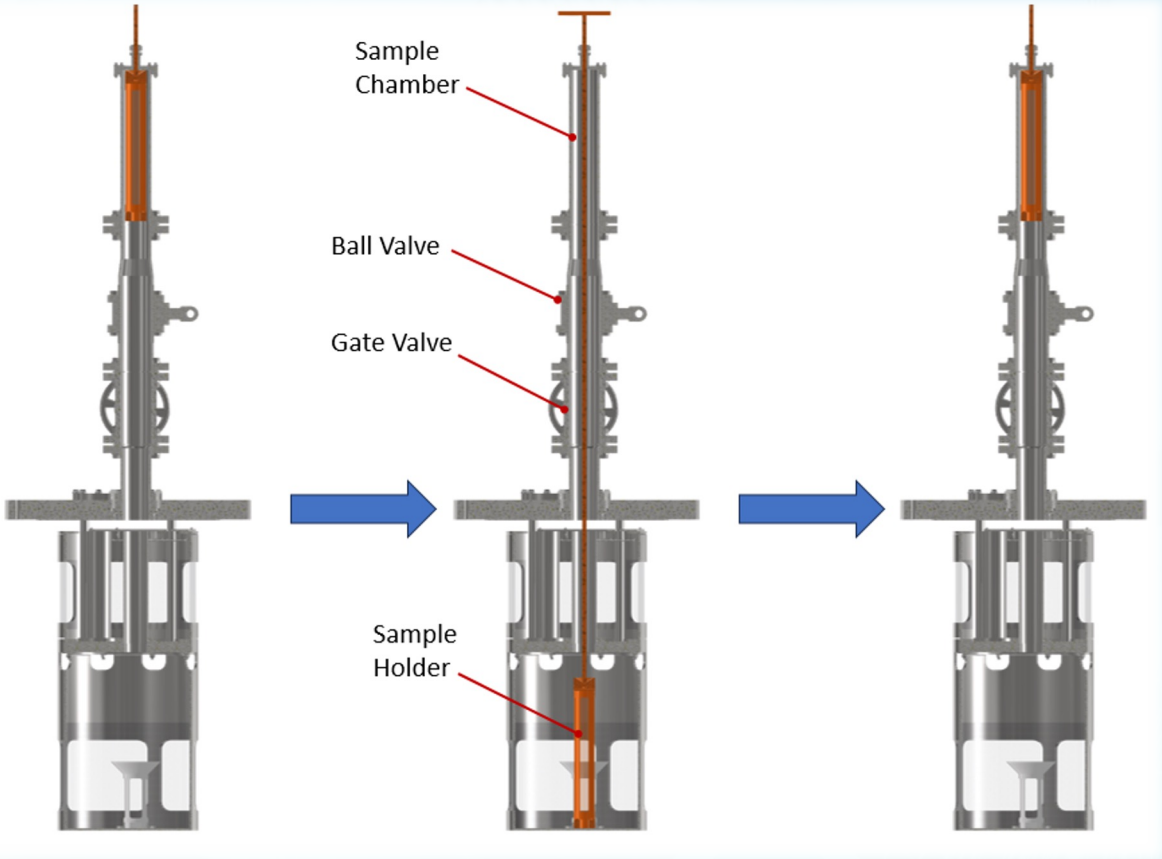
5 liter/min

0.1 liter/min

ANL's Sodium Extraction System

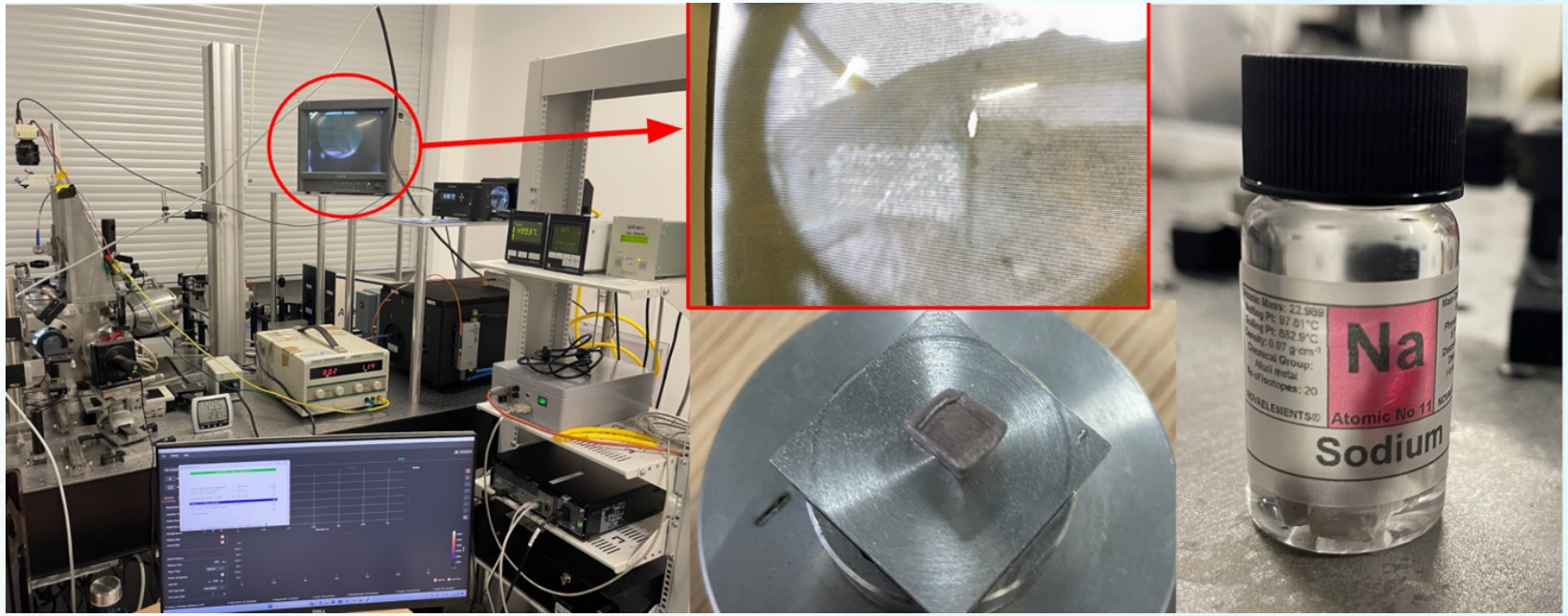
- The clean sodium from METL will serve as a reference material that can be incrementally contaminated by adding solid sodium hydroxide to study impurity behavior
- ANL will use the Sample Test Basket, Two-Valve Port, and Sample Grabber to pull a sodium sample from the METL inventory





Collaboration with Aix Marseille University

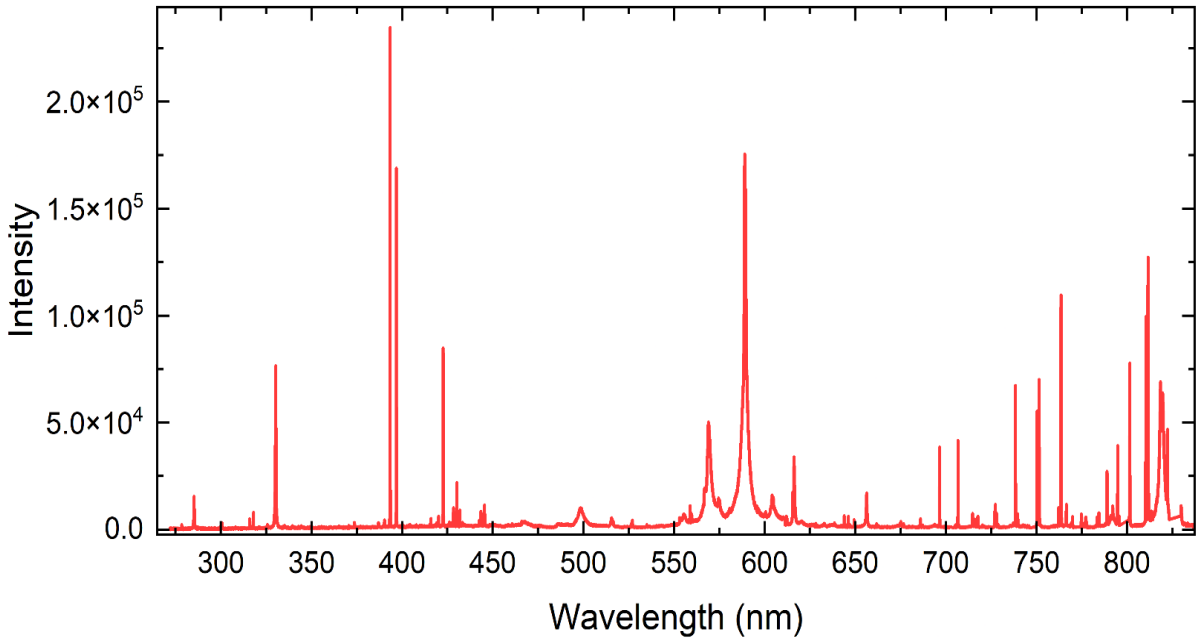
- The laboratory setup at Aix-Marseille University and the rasterized laser irradiation pattern on the sodium sample surface are shown
- Experiments in Ar using both oxidized and non-oxidized samples, with oxidation achieved by exposing the sample surface to ambient air
- Foreign collaborators: Dr. Jörg Hermann, Dr. Vincent Gardette

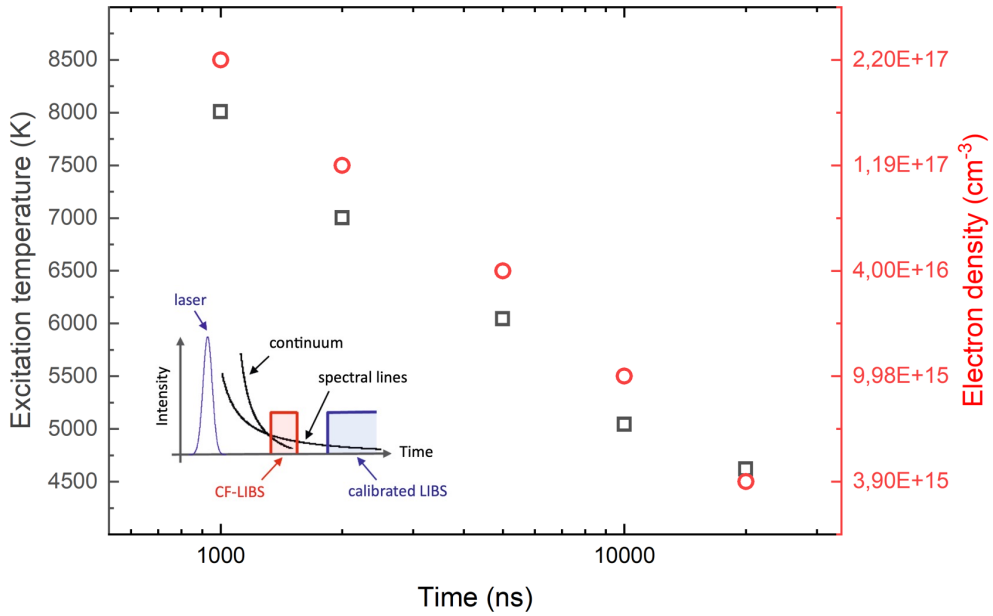


Aix*Marseille université

Collaboration with Aix Marseille University

- Broadband spectral analysis of sodium at various time delays following the laser pulse aims to characterize plasma parameters and quantify trace impurity levels using Calibration-Free Laser-Induced Breakdown Spectroscopy*.





*CF-LIBS; see *Hermann et al. (2017) PRE* & *Hermann et al. (2023) SAB*

Concluding Remarks

- **High-selectivity, fast, direct, and robust sensing capability**
- **Accomplishments:**

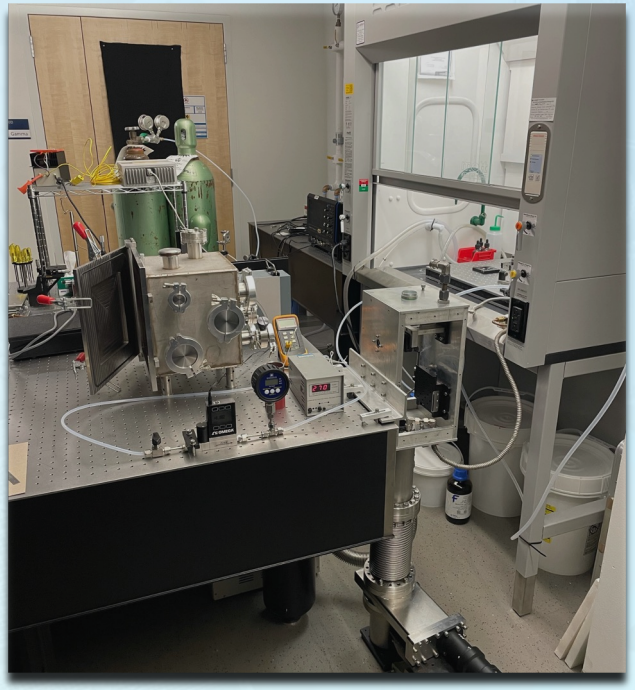
✓ Procured optics, test material and cover gasses in FY24

✓ Constructed and validated the experimental testbed in FY24

- **Plans:**

○ SNR and LOD enhancement strategies in FY25

○ The goal: ppm-level sensitivity and deployment at METL in FY26



- **Publications:**

1. M. Ortiz, E. Kent, J. Craparo, R. De Saro, I. Jovanovic, M. Burger, "Laser-Spectroscopy Testbed Design for Impurity Monitoring in Sodium-Cooled Fast Reactors", Transactions of the American Nuclear Society, 130(1): 357-358 (2024).
2. A. Burak, L. Frigerio, J. Brown, E. Kent, J. Craparo, I. Jovanovic, R. De Saro, and M. Burger, "Laser-Spectroscopy Testbed for Impurity Monitoring in Liquid Metal-cooled Fast Reactors", *submitted for peer review*

Funding: U.S. DOE under Award Number DE-NE0009403
Program manager: Daniel Nichols

NEUP Nuclear Energy University Program
U.S. Department of Energy

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Thank You