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

ASI Advanced Sensors and Instrumentation

Metamaterial Void Sensor for Fast Transient Testing

Phase II SBIR DE-SC0018808

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

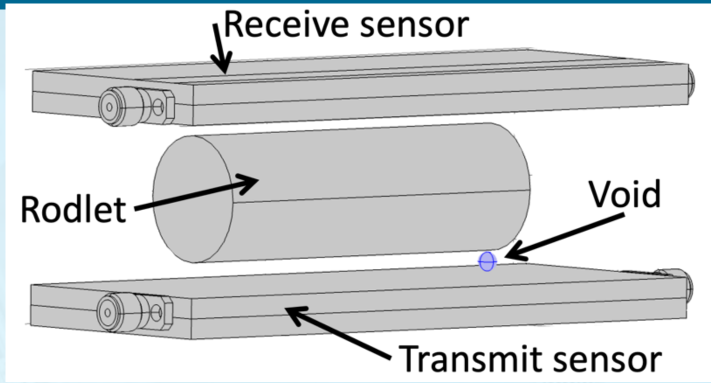
October 24 – 27, 2022

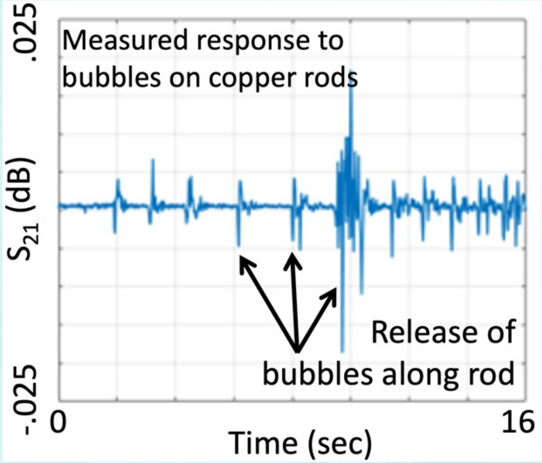
President: Mark W Roberson, PhD PMP

Goldfinch Sensor Technologies and Analytics LLC (GSTA)

Project Overview

- Research scope – Develop and demonstrate "Direct, time-resolved and multi- position detection and characterization of boiling in high-pressure, high-temperature environments with minimal electrical feedthrough requirements."
- GSTA's technology uses RF sensing of the void-induced impedance changes to localize and time-resolve void formation.
- The project received a No-Cost-Extension and delivered parts for TRL 6, in-core testing of key RF elements at INL TREAT during reactor operation.
- Due to internal organizational issues at INL, possible testing will be delayed past the Period of Performance (end of December, 2022) of the SBIR project.





Project Overview – Participants

- GSTA
  - PI: Mark Roberson
  - Staff: Charles Bartee, Kate Frohman, Eric Wagner, Joseph White
  - Students: Brian Alonso[2], William Arana[2], Isaac King[2], Grant Robertson[2], Russell Robertson[2], Davis Roper[1]
- Virginia Tech
  - Sub-awardee lead: Juliana Pacheco Duarte
  - Students: Bruno Pinheiro Serrao[2], Evelyn Washburn[1]

Names in each sub-bullet are listed alphabetically

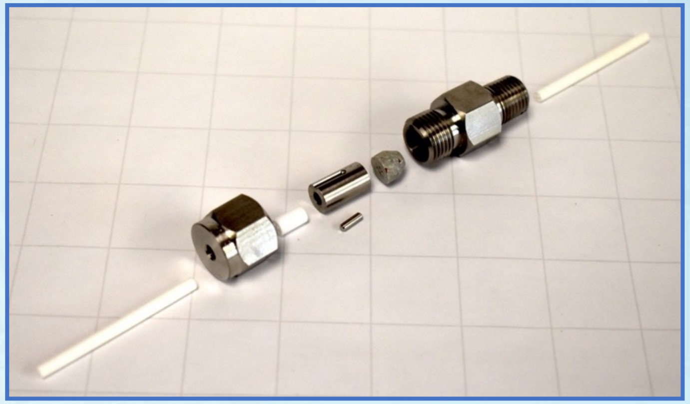
[1]Graduate student
[2]Undergraduate student

The project has supported 8 students at the undergraduate and graduate levels, including design of equipment, construction of devices, and testing of performance.

- Acknowledgments - the SBIR effort has benefitted greatly with support from DOE/NE and INL
  - ASI program managers
  - INL
    - Pattrick Calderoni, Kara Cromwell, Austin Fleming, Colby Jensen, Kevin Tsai, Nicolas Woolstenhulme
  - CAP services from LARTA
    - Gunjan Siroya

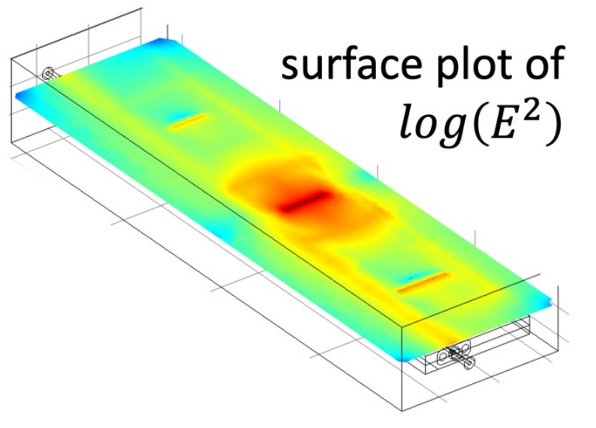
Technology Impact - more rod data with fewer connectors

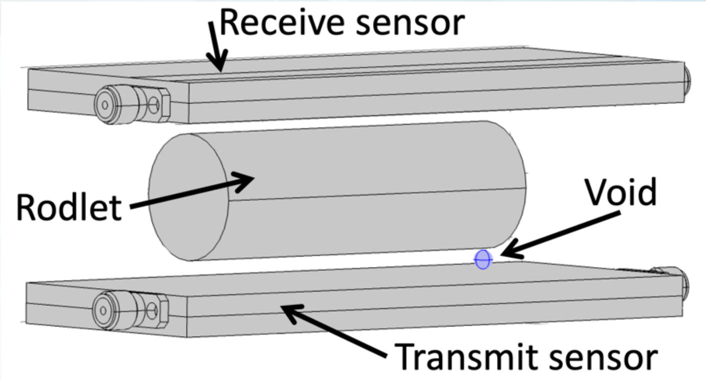
- Present - use DC capacitive plates to measure voids from effective dielectric constant change. More sensing locations means more feedthroughs.
- GSTA's method: two ports in order to sense ten or more locations with high time-resolution and has potential for differentiating between different bubble size distributions.
- GSTA's technology works at both high pressure and high-temperature, making the technology applicable for in-core instrumentation and supporting the nuclear energy industry.

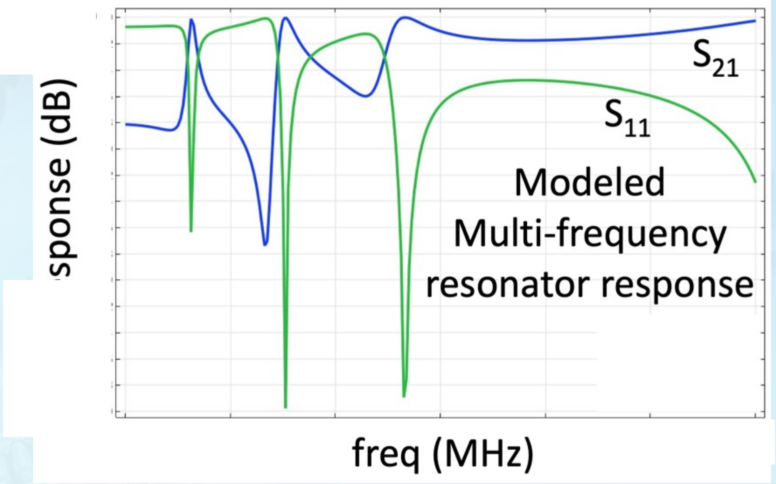


Minimizing the required sensor electrical feedthroughs is critical for experimental design

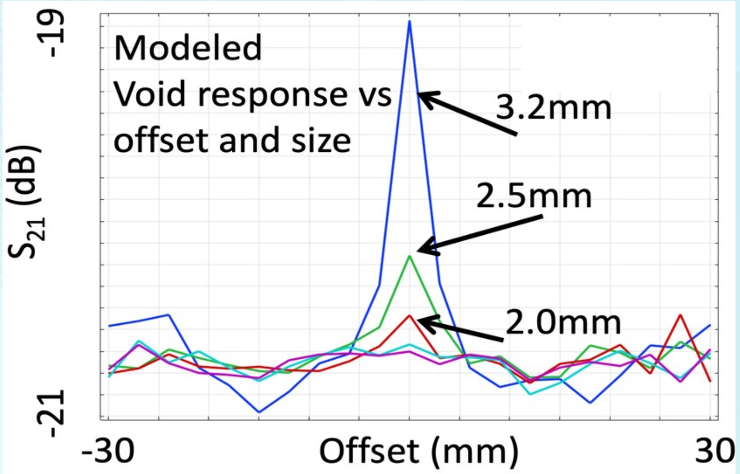
Results and Accomplishments – RF simulation, modeling, and experimentation







Clockwise from top left: electric field calculations at the sensor surface; model including rodlet, sensor, and void; frequency response of the sensor set; predicted spatial response of the sensor to a single void



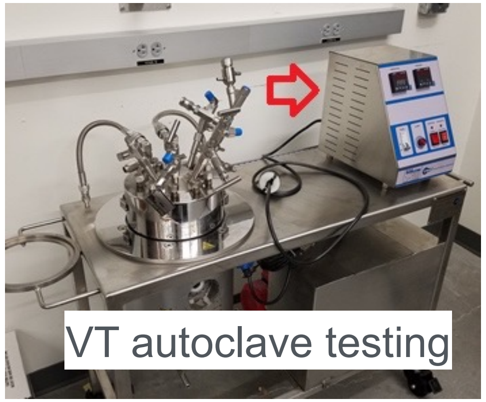
- GSTA conducted extensive RF modeling and simulation of details of void sensing using both COMSOL and MATLAB
- GSTA's modeling work was consistent with previous experimental measurements; the experiments were more sensitive than the FEM uncertainties
- GSTA conducted extensive modeling of the RF feeds from the sensor electronics to the sensor element in the core

Results and Accomplishments – system validation: pressure, temperature

- Part of the SBIR Phase II project was to test the operation of sensor elements parts in operational conditions.
- GSTA and VT have tested parts at high temperatures and at high pressures.
- The original effort did not include neutron irradiation testing nor operation while under neutron irradiation at high temperatures, but GSTA discussed with INL concurrent testing at TREAT.

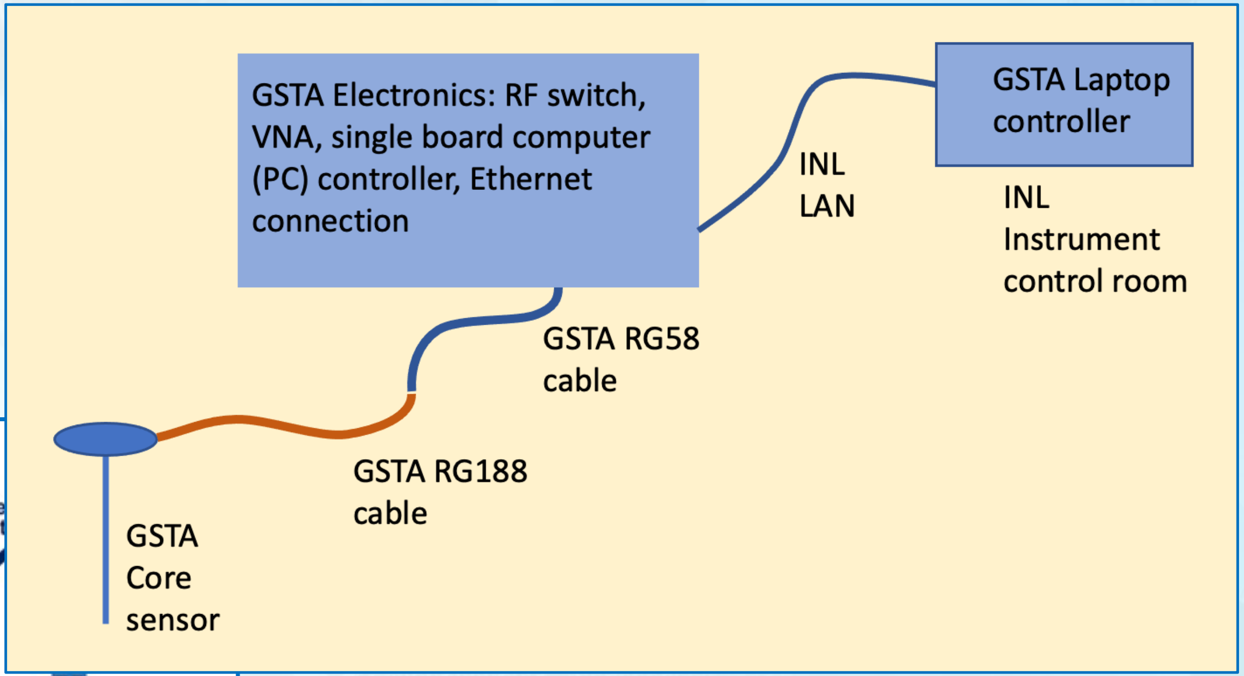
Source	Pressure			Temperature Temperature			Bubbles			Neutron Flux
(conditions)	15PSI, .1MPa	3 kPSI, 21Mpa	kPSI, 34Mpa	300F, 150 C	575F, 300C)	932F, 500C	.5mm	3mm	10mm	> 10^{10} n/cm³/s
GSTA lab	✓			✓	✓	✓	✓	✓	✓	
VT lab	✓	✓		✓	✓		✓	✓		
TREAT cooling channel	✓			✓	✓	✓				✓
TREAT / test cell	✓	✓	✓	✓	✓	✓	✓	✓		✓

GSTA kiln testing


VT autoclave testing

Results and Accomplishments –
GSTA-TV1 Irradiation experiment –geometry

- GSTA designed the sensor to insert into a TREAT interstitial cooling channel
- The RF electronics operate in the bay, controlled remotely by a laptop




SBIR PHASE II DE-SC0018808

GSTA-TV1 Test plan
v1.1
December 2021

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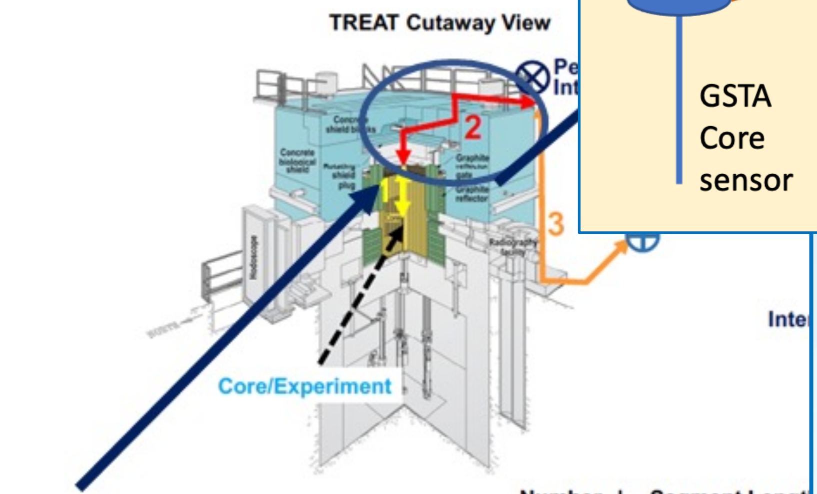


Approximate placement area of GSTA-TV1 sensor

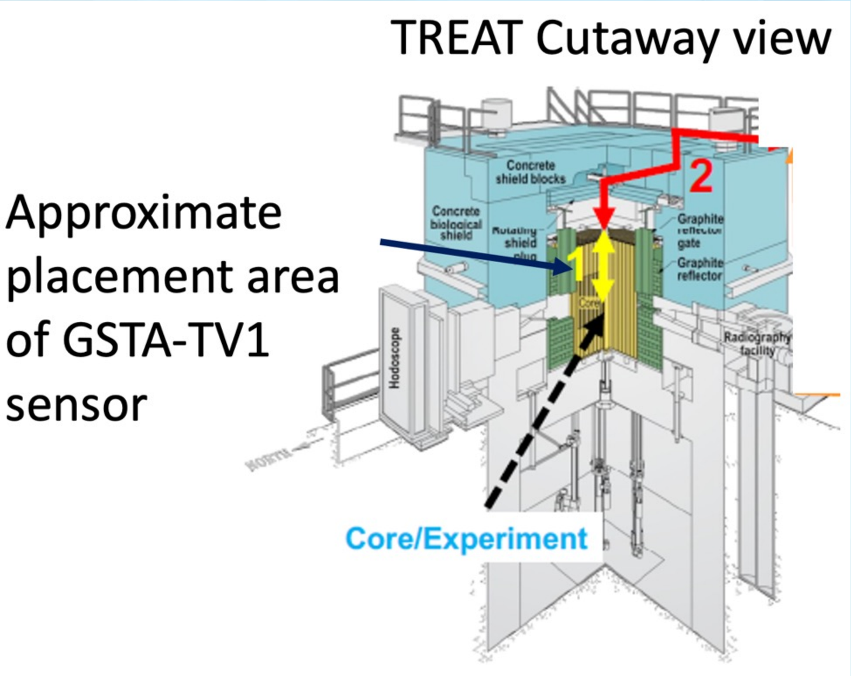
Number	Segment Lengt
1	1.5
2	10
3	11

Note: the GSTA-TV1 test plan has extensive details of the sensor hardware

Results and Accomplishments

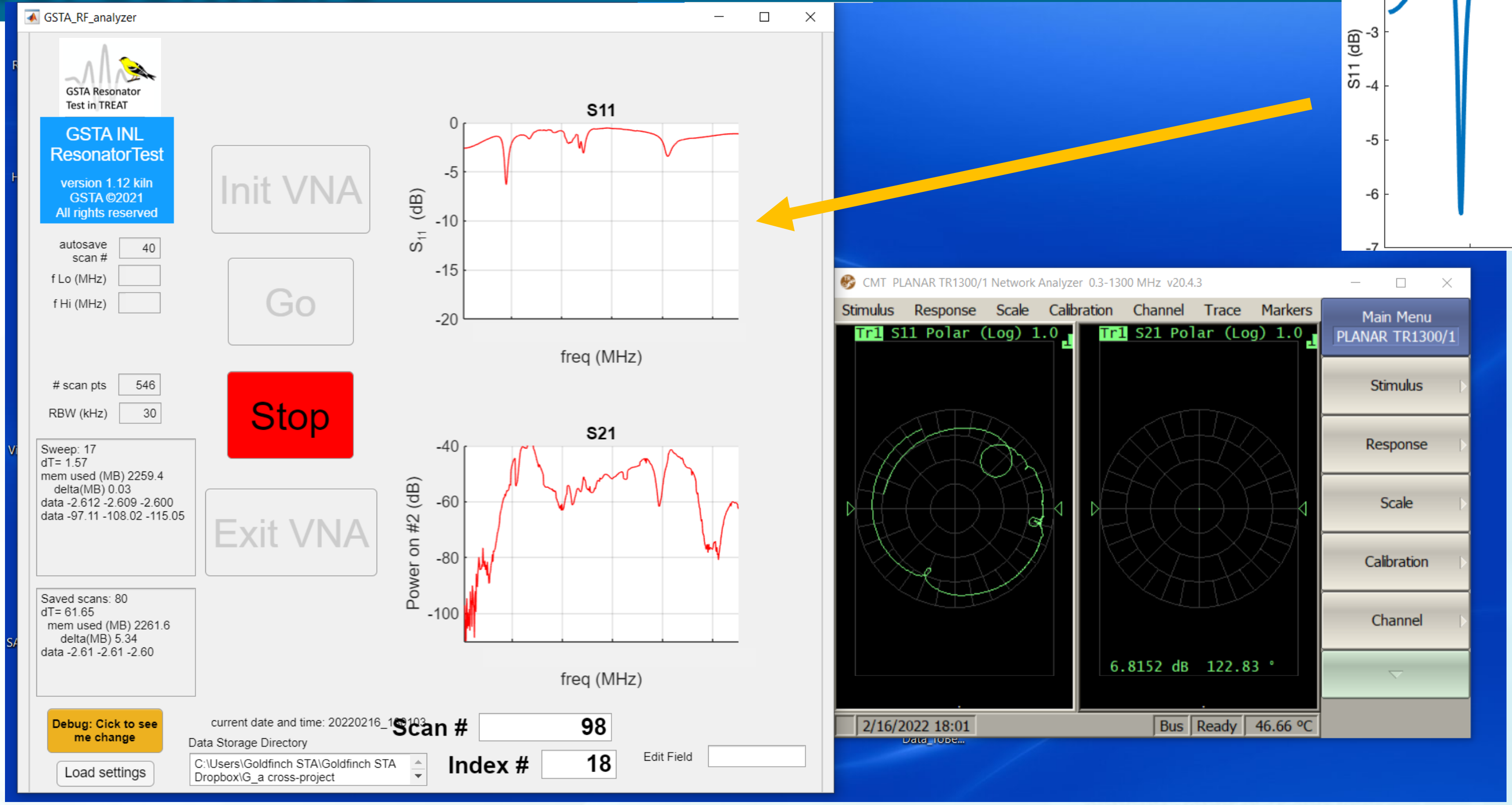
- GSTA discussed with INL testing of the SBIR Phase II parts at TREAT but testing the full-sized void sensor was not feasible.
- INL offered to include a GSTA sensor on a non-interference basis in a TREAT reactor core interstitial during irradiation experiments.
- An in-core test requires agreement at multiple levels and across INL groups. GSTA made it past technical, but the effort was held up by Operational Configuration Management requirements after design and delivery.

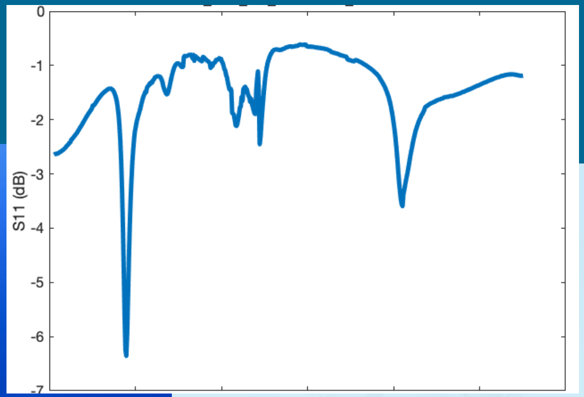
- GSTA still has hope of validating key elements of the sensor design in an interstitial channel after the Phase II effort period of performance



Results and Accomplishments – GSTA-TV1 control software

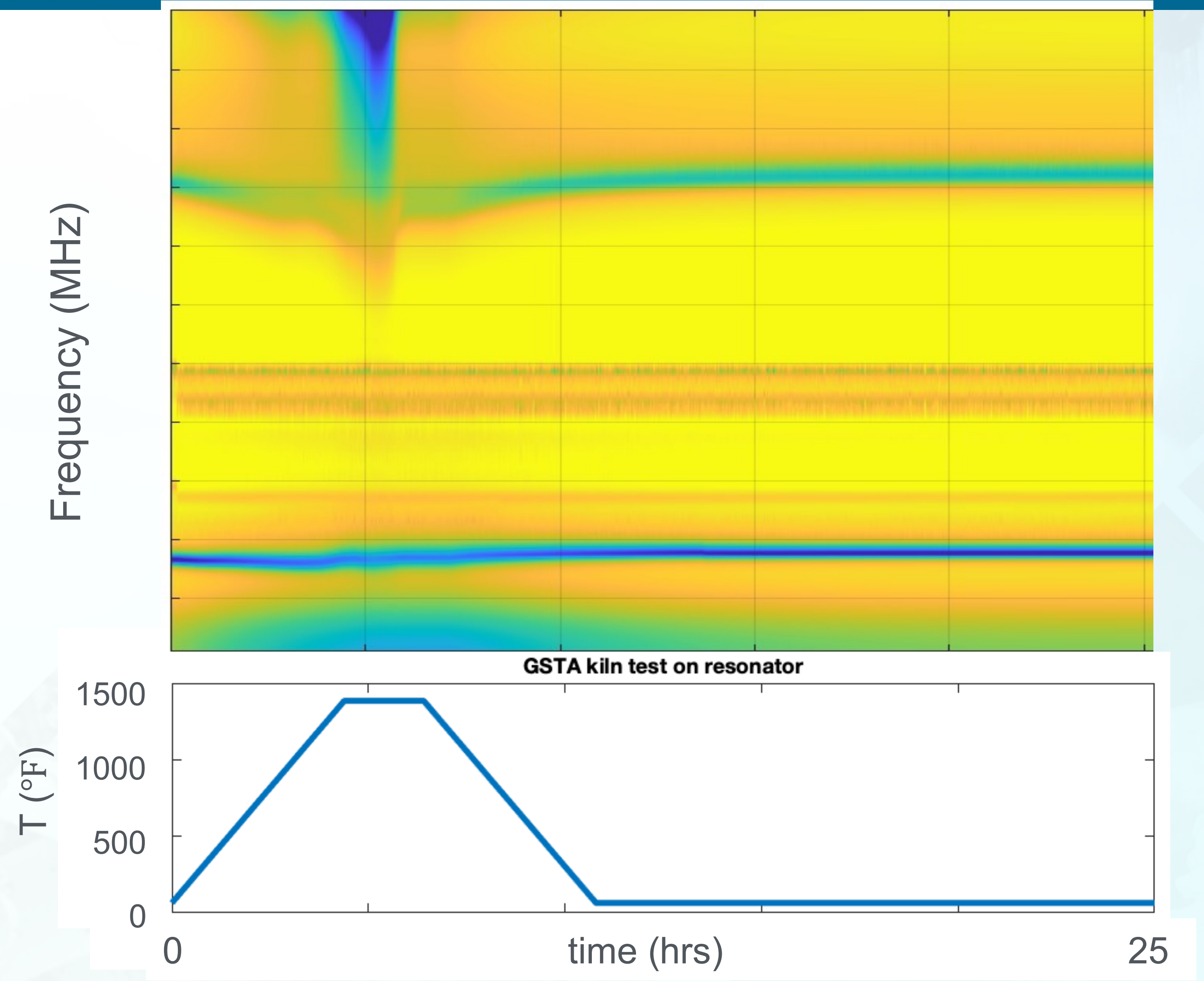
The user screen also shows diagnostic information to aid in "long distance troubleshooting"





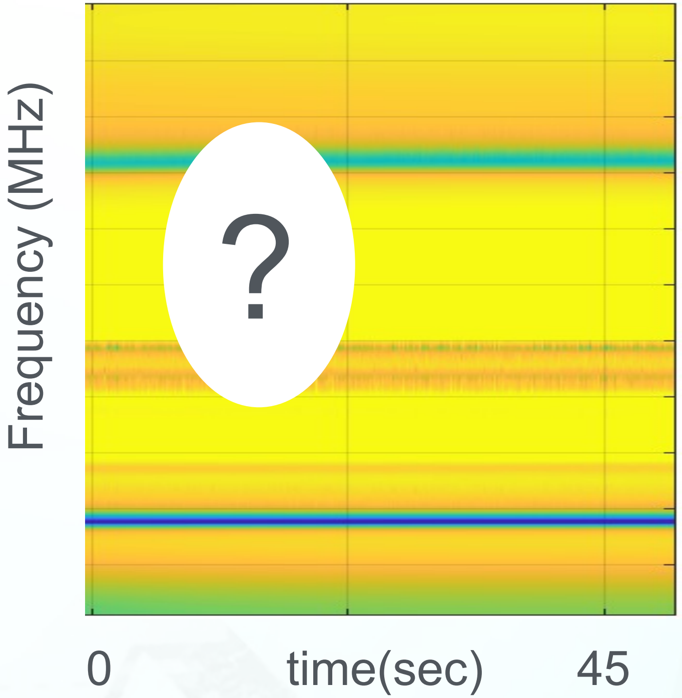
- GSTA's control software is designed to be run remotely by INL staff, with a simplified "Go/Stop" button userface, with memory management to allow the software to run longer than 24 hours without user intervention, and automatic data saves approximately every minute.

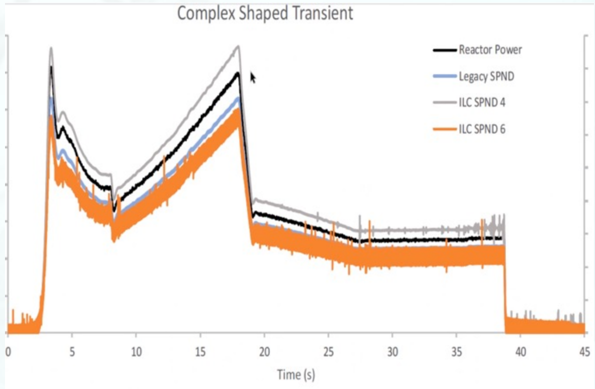
Results and Accomplishments – GSTA resonator kiln Data



- GSTA monitored a resonator similar to the GSTA-TV1 element in a kiln
- The peak temperature of 1385°F (750°C) was chosen to understand the performance in a molten salt reactor (MSR) thermal environment
- GSTA found that in our test set-up, a higher frequency range becomes unusable while at temperature, but our resonator frequency continued to work

Results and Accomplishments – GSTA-TV1 plan for concurrent testing





- What happens to the resonator when irradiated?

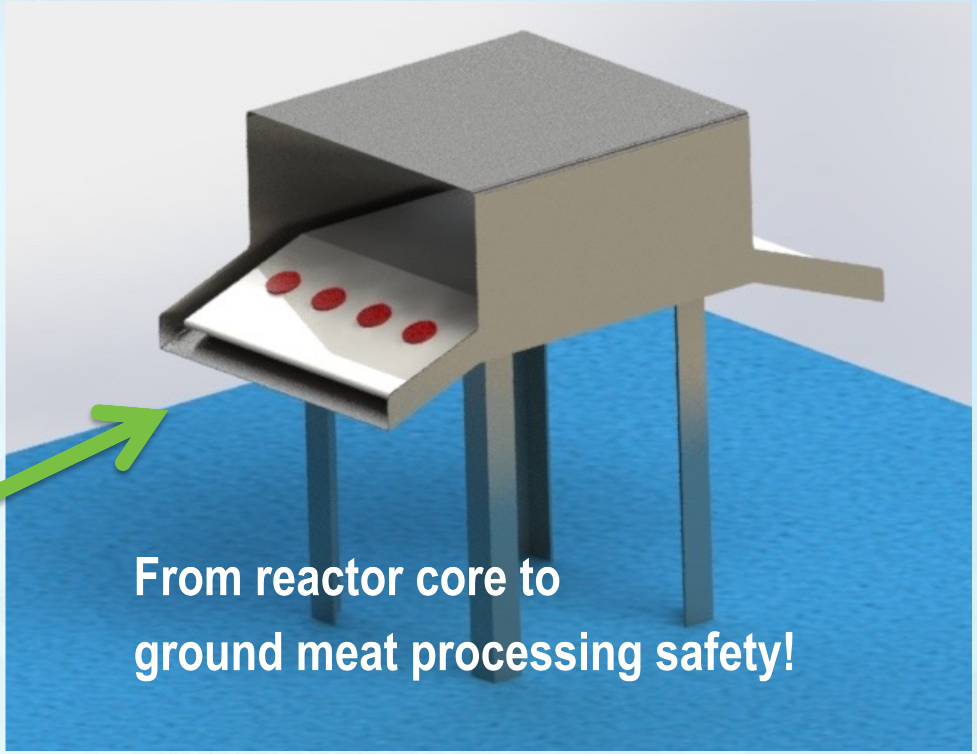
1. Does it survive?
    1. Thermally, we know it will
2. Does the resonator frequency change?
    1. We believe it will change due to thermal issues but not neutron flux
3. Does the noise floor increase?
    1. WHERE THE FUN STARTS
    2. Mechanical-electrical, time-of-flight, quantum current, temperature + quantum noise

Concluding Remarks - summary

- GSTA and its partner VT are completing a Phase II SBIR for rodlet void measurement.
- The Phase II conducted validation and verification of key sensor elements.
- Key technologies: void sensing, sensor size minimization and reduction of feedthroughs by 10x.
- The total void sensing package exited at Technology Readiness Level 5 (TRL5) with GSTA laboratory testing in relevant environment and interfaces.
- GSTA’s RF sensor elements exit at TRL 6 when TREAT testing is conducted.

Concluding Remarks

- Harvesting: potential applications
  - Reactor core instrumentation for distributed, multi-point sensing of neutron flux
  - Non-nuclear:
    - Down hole oil and carbon storage wells
    - On-orbit and re-entry vehicle sensors
    - Pharma – T-cell personalized medicine
    - USDA – meat and poultry processing safety
- Intellectual property (IP) portfolio generated
  - RF circuit designs
  - Sensing algorithms
  - Fabrication process flow
  - Software design
  - Held as trade secrets presently



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Thank You