Radiation Hardened Electronics

Johnson Noise Thermometry

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

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Oak Ridge National Laboratory

RHE at ORNL (Nuclear Focus)

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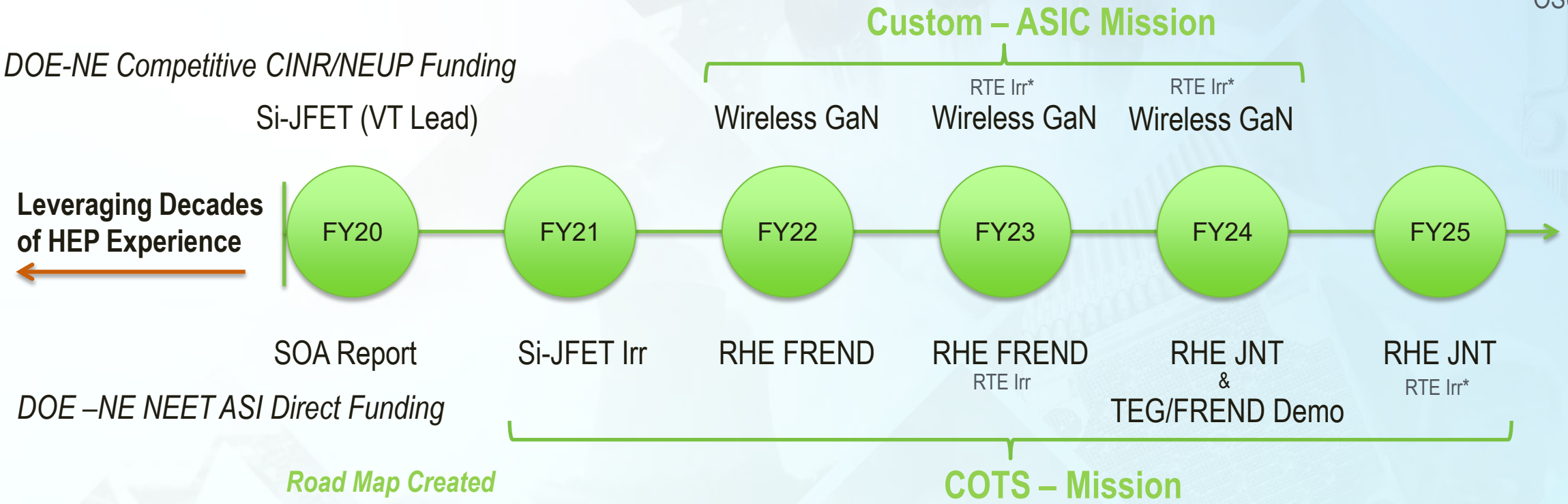
Dan Sweeney; Callie Goetz; Pat Mulligan; Dianne Ezell
DoD: Brandon Wilson

*OSU Irradiations



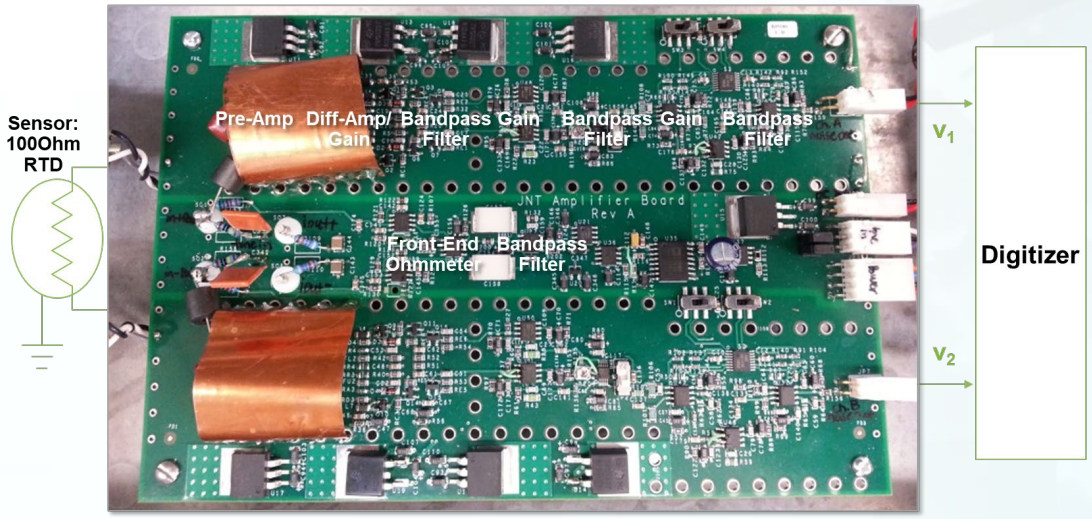
DOE Office of Science (Fusion)

- FY18/19: ITER: development of RHE for vacuum systems* (Ericson)
- FY21: ITER: evaluation of embedded electronics in instrumentation* (Mulligan/Ezell)

Project Overview: RHE Johnson Noise Thermometry

- Implementation of Johnson Noise Thermometry (JNT) into Radiation Hardened Electronics (RHE) – This task focuses on JNT, which has been proposed for space reactors and SMRs as a self-calibrating thermometry system, reducing maintenance costs and increasing reliability.
- The electronics used in this system were developed at ORNL and the front-end low-noise amplifiers are JFET based making this a prime candidate for RHE development using commercially available parts.
- Project completion **delayed** to FY25 – commercial parts arrived at ORNL Sept. 2024
  - *M3CT-24OR0702062* Task 1: Develop RHE JNT using MAGICS Technology semi-custom front-end electronics and RdF resistance temperature device (RTD)
    - Demonstrate low-noise electronics in “clean” lab environment
    - Demonstrate low-noise electronics in “noisy” lab environment
    - Demonstrate low-noise electronics in “radiation” environment (OSURR using RTE)
  - *M3CT-24OR0702061* Task 2: Integrate Notre Dame developed TEG with FREND RHE: **Completed 04/2024 – M3 available in PICS**
- Participants: Kyle Reed; Dan Sweeney; N. Dianne Bull Ezell
  - TEG/FREND demonstration: Callie Goetz, Md Omarsany Bappy; Yanliang Zhang

Project Overview: RHE Johnson Noise Thermometry



What is JNT?

- JNT is the application of **custom front-end electronics** and **signal processing** to a RTD and acquire an averaged signal over time that can be used for self-calibration of proximally close RTDs from neutron degradation
- Adopted by metrology community for calibration of temperature sensors

1970

- Resistance and noise voltage critical for JNT measurement
- Amplifier Electronics designed and noise accounted for in system
- Became aware of EMI contributions to noise but no spectral analysis of time-domain quality checks developed yet.
- Bob Shepard & Vaughn Blalock continue developments on JNT

Early 1970's

- HFIR operators wanted to measure fuel centerline temperatures of the center rod in the core.
- I&C division provided Tungsten-Rhenium thermocouple to measure temperatures of 1500 °C.
- Within days temperature drift were noticed in the system.
- Vaughn Blalock & Cas Borkowski developed first JNT implementation at ORNL.

Mid-Late 1970's

1977

- R&D 100 Award: "Johnson Noise Power Thermometer"

1980

Mid 1980's

- Mike Roberts joined the project to develop signal processing.
- Several methods developed
  - Sensor in parallel with capacitor eliminating sensor resistance dependence of system. (needed large bandwidth and no EMI)
  - Sensor in parallel with LC tuned circuit narrowing the spectral range and reducing bandwidth. (ideal inductors needed and still no EMI compensation)

1990

Early 1990's

- Correlation techniques and spectral analysis integrated into signal processing. (Eliminates amplifier noise and detects/rejects periodic EMI)

2000

2002

- Joint – US Korean Nuclear Energy Research Initiative Program
- Correlation Measurement

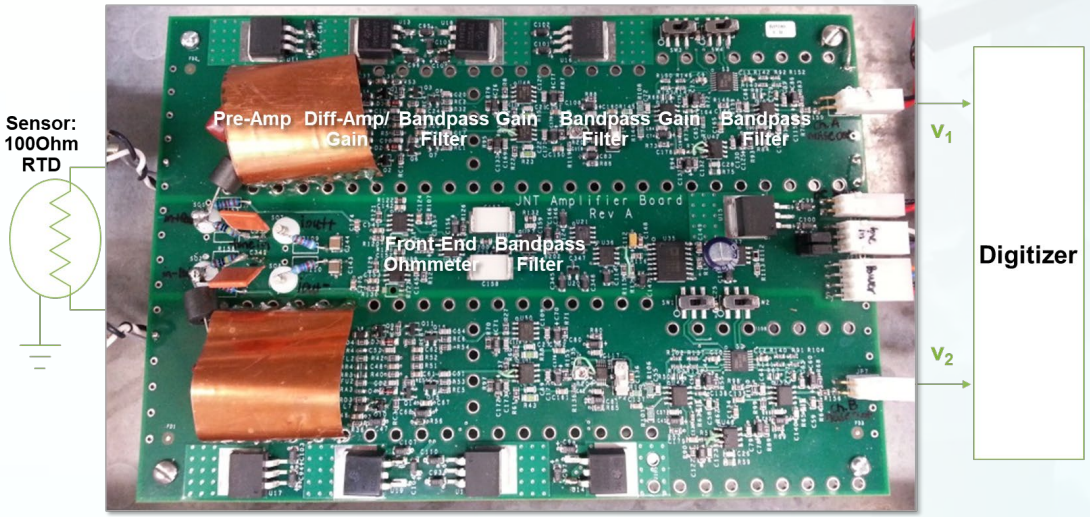
2010

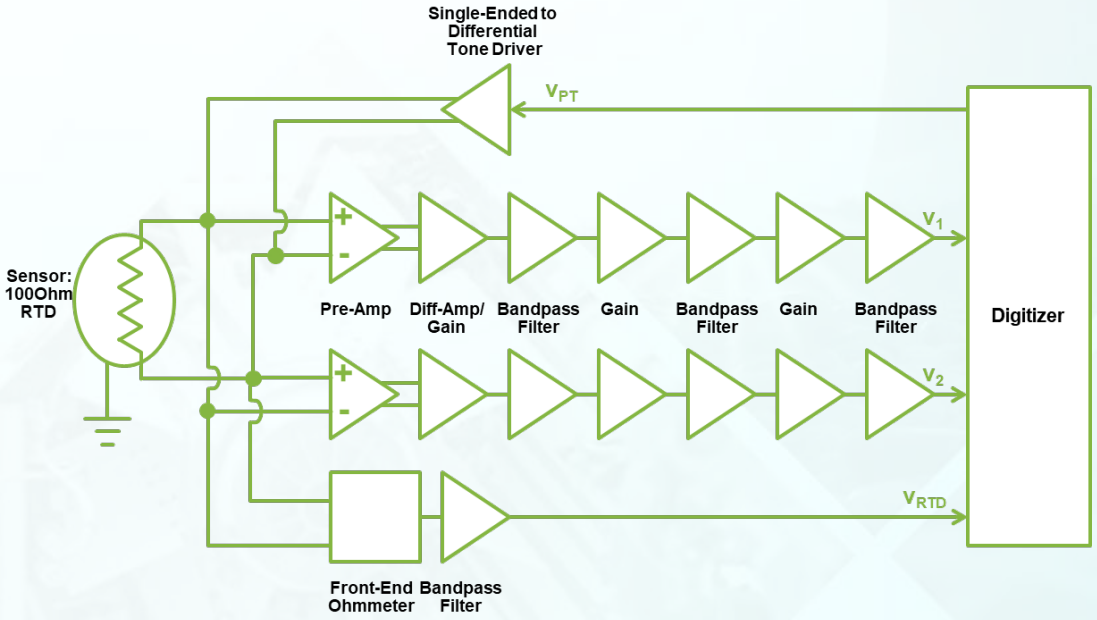
Signal (still) sensitive to noise injected on cable

2012

- 2012 Johnson Noise Thermometry for Advanced Small Modular Reactors

Project Overview: RHE Johnson Noise Thermometry



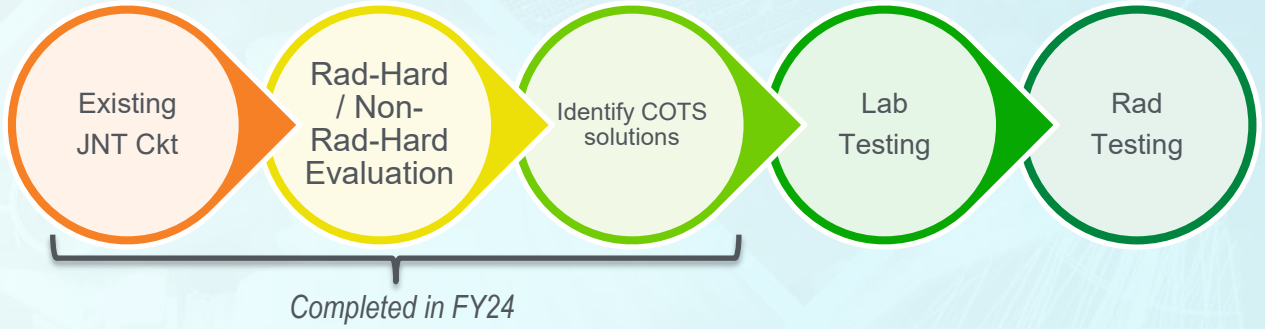


What is JNT?

- JNT is the application of **custom front-end electronics** and **signal processing** to a RTD and acquire an averaged signal over time that can be used for self-calibration of proximally close RTDs from neutron degradation

Why rad-hard JNT?

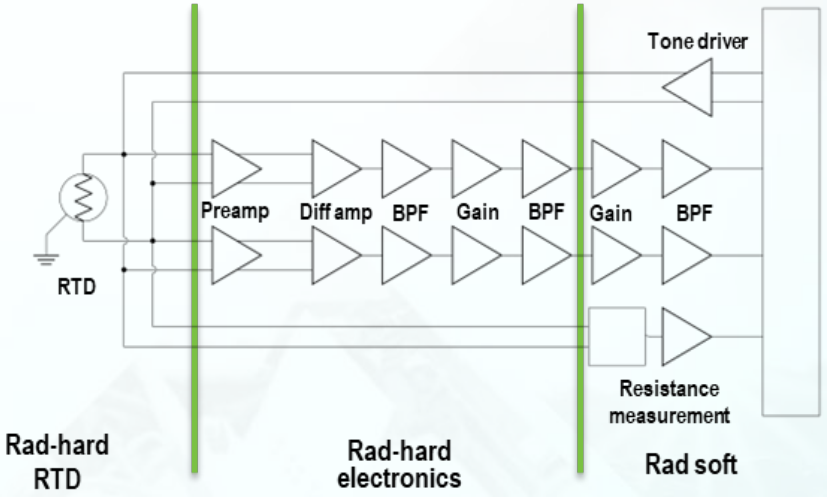
- Susceptible to noise injection on cable – locating pre-amp and diff-amp as close to sensor as possible strengthens the application



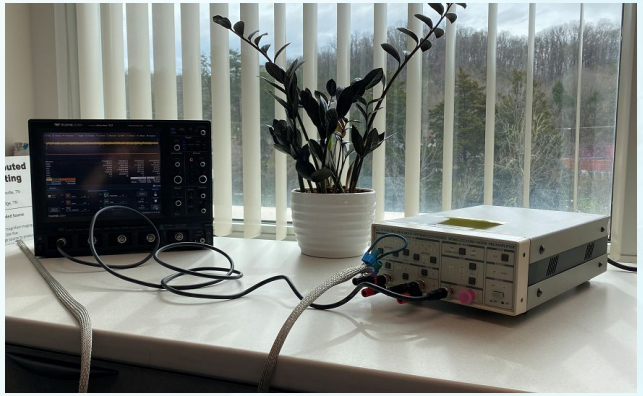
RHE-JNT approach

Project Overview: RHE Johnson Noise Thermometry

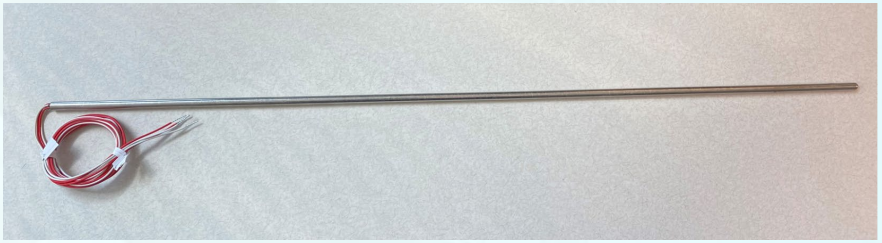
1. Define the design: ORNL
2. (Donated) Rad-hard RTD: RdF
3. (Acquired) Rad-hard pre-amp with gain: MAGICS Tech



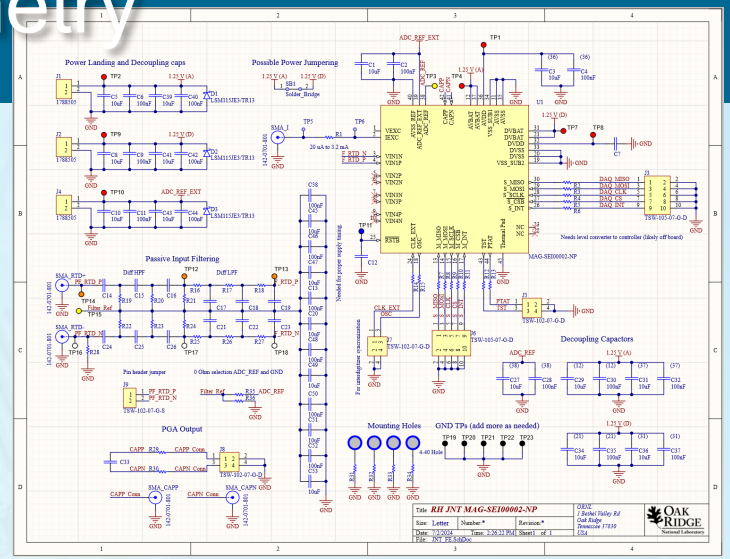
1. RHE-JNT approach

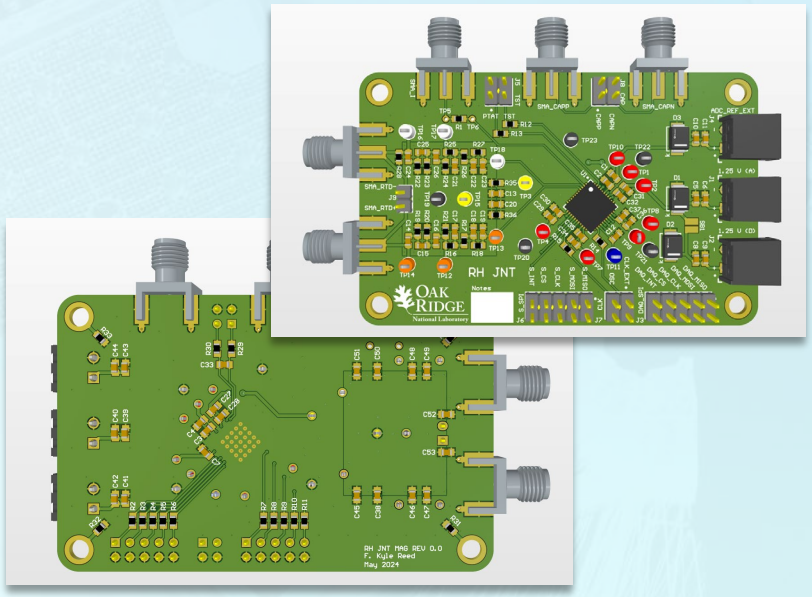


Simple Laboratory JNT System using commercial amplifiers (rad-soft)



2. Commercial 100 Ω RTD





1. & 3. Printed circuit board featuring a radiation-hardened (gamma) amplifier and DAQ

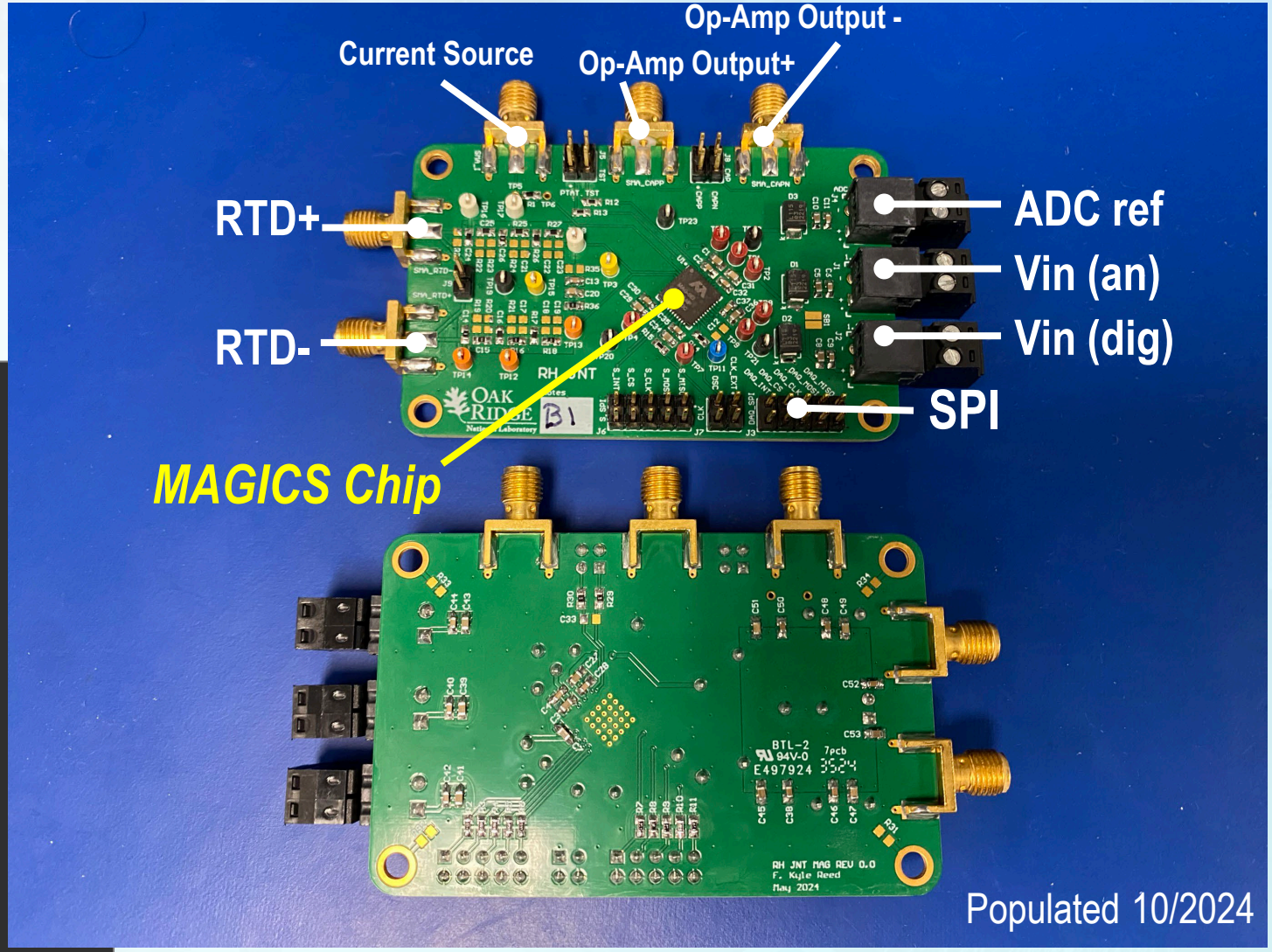
Project Overview: RHE Johnson Noise Thermometry

```c
/*
 * magicsMAGSEI00002NP.c
 *
 *  Created on: Oct 23, 2024
 *      Author: 1c9
 */
#include "magicsMAGSEI00002NP.h"
#include <stdint.h>

static void __magics_sendSPI__(const struct magics_driver *dev, uint8_t addr, uint8_t rw, uint8_t com
    uint8_t transmit[] = { addr | rw, command_word};
    HAL_GPIO_WritePin(dev->gpio_bank, dev->cs_pin, GPIO_PIN_RESET);
    HAL_SPI_TransmitReceive(dev->spi_device, transmit, receive, 8, 1);
    HAL_GPIO_WritePin(dev->gpio_bank, dev->cs_pin, GPIO_PIN_SET);
}

void magics_Init(struct magics_driver *dev, SPI_HandleTypeDef *hspi, GPIO_TypeDef *gpio_bank, uint16_
    /* Populate device driver struct */
    dev->spi_device = hspi;
    dev->gpio_bank = gpio_bank;
    dev->cs_pin = cs_pin;

    __magics_sendSPI__(dev, MAGICS_REG0, MAGICS_REG_READ, 0
}

void magics_EnableInternalClock(const struct magics_driver
    uint8_t receive[2];
    __magics_sendSPI__(dev, MAGICS_REG29, MAGICS_REG_READ,

    uint8_t new_reg = receive[1];
    new_reg |= MAGICS_REG29_EN_clock;
    __magics_sendSPI__(dev, MAGICS_REG29, MAGICS_REG_WRITE,

    /* Wait until stable */
    HAL_Delay(MAGICS_STARTUP_DELAY);
```

```c
/*
 * magicsMAGSEI00002NP.h
 *
 *  Created on: Oct 23, 2024
 *      Author: 1c9
 */

#ifndef INC_MAGICSMAGSEI00002NP_H_
#define INC_MAGICSMAGSEI00002NP_H_

#include "stm32h7rsxx_hal_spi.h"

#define MAGICS_STARTUP_DELAY 100

#define MAGICS_REG_READ 1
#define MAGICS_REG_WRITE 0


#define MAGICS_REG_BIT 1

/* Magics Chip Register Function Aliases*/
/* REGISTER 0 (0x00) */
#define MAGICS_REG0 (0x00 << MAGICS_REG_BIT)
#define MAGICS_REG0_METAL_VERSION 0x03
#define MAGICS_REG0_DIGITAL_VERSION 0x0c
#define MAGICS_REG0_Chip_id 0xf0

/* REGISTER 1 (0x01) */
#define MAGICS_REG1 (0x01 << MAGICS_REG_BIT)
#define MAGICS_REG1_int_new_sample 0x01
#define MAGICS_REG1_int_external_sens 0x02
#define MAGICS_REG1_BIST_CONT_ERROR 0x04
#define MAGICS_REG1_BIST_ONDEMAND_ERROR 0x08
#define MAGICS_REG1_int_autotoggle_ch1 0x10
#define MAGICS_REG1_int_autotoggle_ch2 0x20
#define MAGICS_REG1_int_autotoggle_ch3 0x40
```

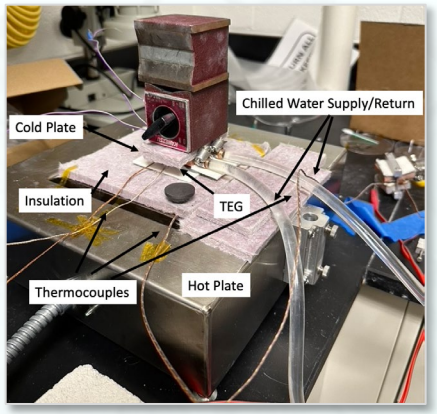
Software package:

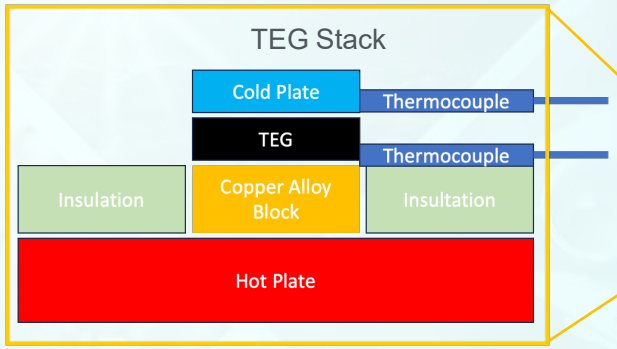
- Acquire real-time and JNT signal
- Compare two signals for drift
- Calibration real-time measurement from JNT signal

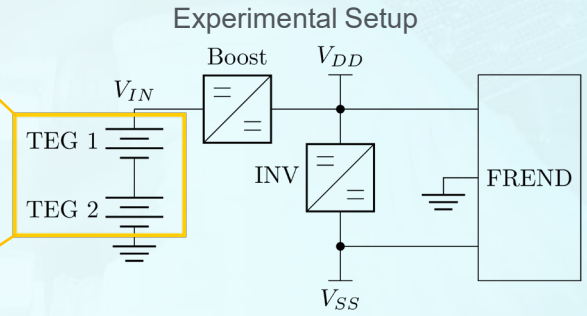


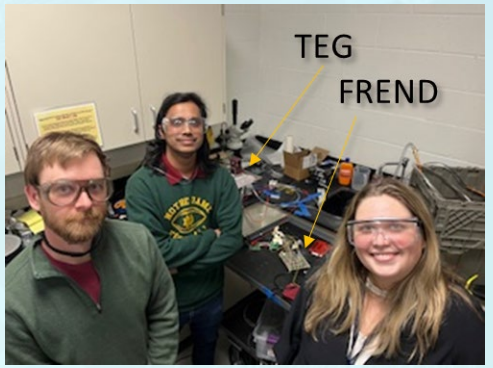
Project Overview: TEG/FREND Demonstration

- **Mission:** Harvest waste heat from nuclear applications (reactors, fuel storage, etc.) to power radiation hardened electronics (FREND) – eliminate need for external power cabling and reduce reactor penetrations
- Impactful collaboration across 2 ORNL Directorates (ESTD & FFESD) and University of Notre Dame
  - Example of National Laboratory raising the TRL of NEUP developed technology within the NEET-ASI program
- Show below, University of Notre Dame developed high power density Thermoelectric Generator (TEG) coupled with ORNL developed Front End Digitizer (FrEnD) for a successful demonstration
- Milestone completed April 2024 and available in PICS









Technology Impact

RHE JNT:

- While JNT was originally developed for HFIR, it is applicable to advanced reactors and development continued under Space and SMR programs
- Microreactors deployed in remote locations, including space programs, will require extended operation periods with minimal-to-no maintenance for the lifetime of the reactor
- Self-calibrating instrumentation will extend the lifetime (and reduce maintenance) of critical sensors
- Radiation hardened electronics allow closer integration of electronics closer to the reactor core/sensors installation – reducing noise and increasing signal integrity (transmitting digital instead of analog signals)

Concluding Remarks

FY24 Accomplishments: (Activity Delayed)

- RHE JNT: circuit designs; PCBs fabricated; RTD (from RdF) characterized
- TEG demonstration: successfully completed TEG/FREND testing; results reported in M3-report

FY25 Scope (CO, no new BA):

- RHE JNT: Bench-top test boards in ”clean” environment; “noisy” environment; and radiation environment
- Possible integration of VALTOK low-noise cable

Additional considerations for industry partners – EC/DC guidance around RHE. Guidance is available with limited distribution (CUI report: CG-MGE-1)

- ORNL actively working with EC/DC reviewers on nuclear reactor technology limitations

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Thank You