Design and Implementation of a Simultaneous Readout High-Accuracy Calibration System for Cryogenic Temperature Sensors

Dawid Siuta, Dominik Nowak, Kamil Kozlowski, Kamil Nowatkowski, Ryszard Duda

FRAKO TERM
Research and Implementation Company

SPAS `24 Kraków 21-24 October 2024

FRAKO-TERM

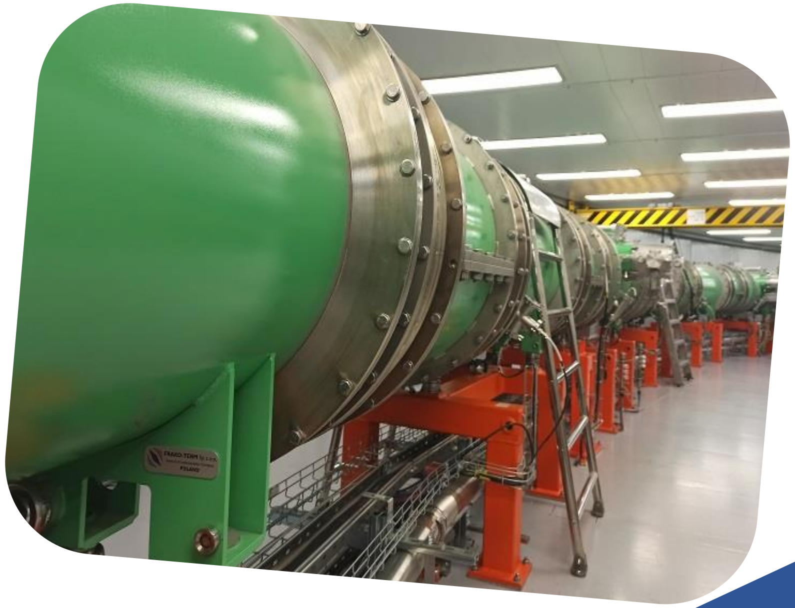
1. About

What do we do?

Research and Implementation Company 'Frako-Term' Sp. z o.o. is a valued private company that has existed since 2004.
We specialize in the use of cryogenic and superconducting technologies in various areas of industry, including for the rationalization of production, storage, and utilization of electrical and thermal energy.

Scope of Activity

We design, develop, and manufacture devices operating in high and ultra-high vacuum conditions, as well as equipment that supports and operates at cryogenic temperatures.
We actively participate in the modernization and expansion of existing experimental infrastructures. We are the main supplier of HV and UHV chambers for the NICA project conducted by JINR in Dubna.



FRAKO-TERM

Key scientific partners

The company has ongoing cooperation with many domestic and foreign centers.

The AGH University of Science and Technology in Kraków, the Institute of Electrical Engineering in Warsaw, the Institute of Communications in Warsaw, the Warsaw University of Technology, and the Joint Institute for Nuclear Research (JINR) in Dubna (Russia).

A comprehensive approach to the implemented topics, as well as openness to innovative technologies, allows us to offer products with high parameters, precisely meeting the needs and expectations of the customer.

2. History of the Calibration System at JINR

Background: JINR

The Joint Institute for Nuclear Research (JINR) in Dubna, Russia, is an international scientific organization, which before 2022 included 18 member states.
In the 1990s, JINR started the construction of nuclotron which required sophisticated cryogenic technology to operate superconducting magnets.

The Original Calibration System for nuclotron

In the early 1990s, a temperature sensor calibration system was created to monitor the superconducting magnets for the nuclotron ring.
The system was necessary to prevent quenching (resistive states) by monitoring temperatures, but it had several limitations.

2. History of the Calibration System at JINR

Measurement Environment:

- Minimum temperature: 1.5K
- Typical cycle time: 8-12 hours
- Output for 23 channels and heating elements

System Capabilities:

- Able to calibrate up to 21 sensors simultaneously (two reference resistors)
- Used heaters to accelerate the process above 80K
- Allowed for switching between two current sources for measurement:
  - Low current: 10 μA for low temperatures (up to 80K)
  - High current: 100 μA for higher temperatures
- Measurement current readout
- Polarity switch (Seebeck effect reduction)

Manual Adjustments:

- Temperature control was done manually via heaters
- The system's accuracy and efficiency depended on the operator's skills, introducing the possibility of human error (gross error detection – purely dependent on the operator)

2. History of the Calibration System at JINR

Measurement Environment:

- Minimum temperature: 1.5K
- Typical cycle time: 8-12 hours
- Output for 23 channels and heating elements

System Capabilities:

- Able to calibrate up to 21 sensors simultaneously (two reference resistors)
- Used heaters to accelerate the process above 80K
- Allowed for switching between two current sources for measurement:
  - ➢ Low current: 10 µA for low temperatures (up to 80K)
  - ➢ High current: 100 µA for higher temperatures
- Measurement current readout
- Polarity switch (Seebeck effect reduction) ⟶

$$V_1 = V_{emf} + V_a - V_b$$

$$V_2 = V_{emf} + V_b - V_a$$

$$\frac{(V_1 - V_2)}{2} = \frac{V_{emf} + V_a - V_b - V_{emf} - V_b + V_a}{2}$$

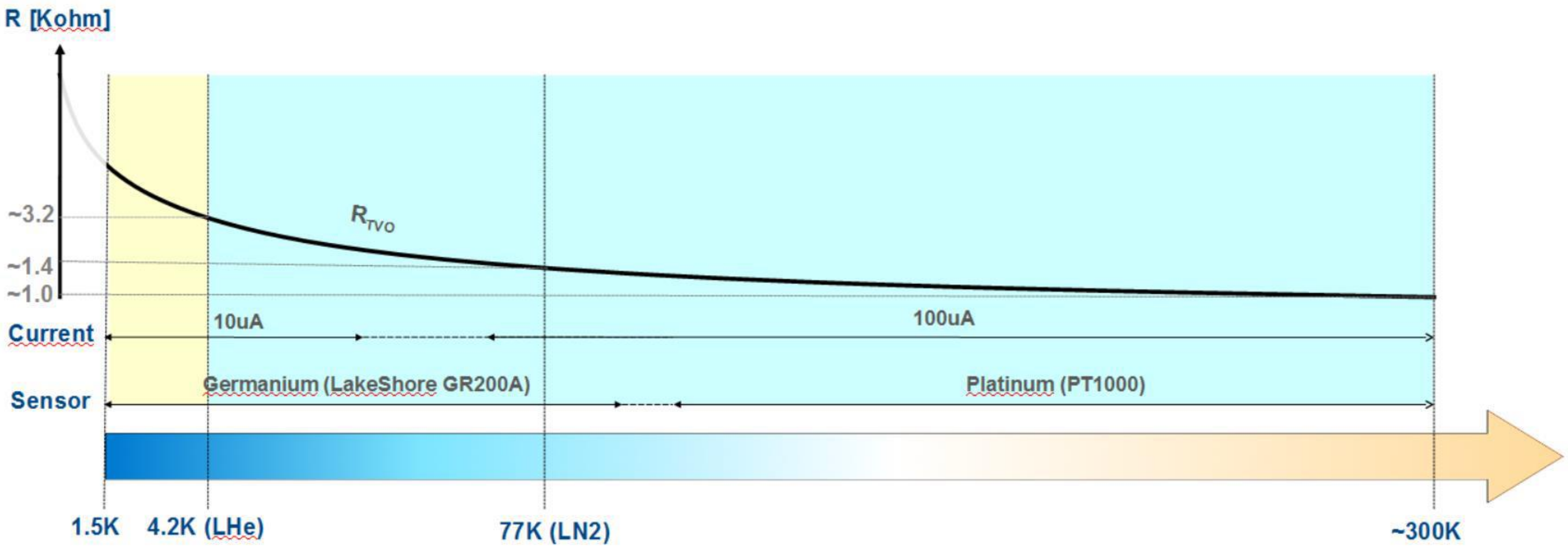
$$\frac{(V_1 - V_2)}{2} = V_a - V_b$$

Manual Adjustments:

- Temperature control was done manually via heaters
- The system’s accuracy and efficiency depended on the operator's skills, introducing the possibility of human error (gross error detection – purely dependent on the operator)

2. History of the Calibration System at JINR

Calibration process



2. History of the Calibration System at JINR

Proglems:

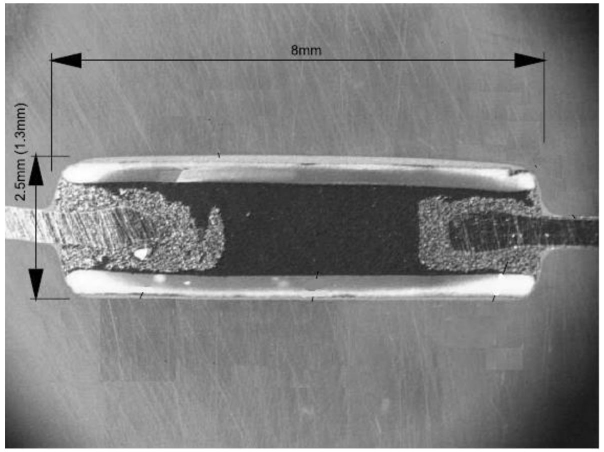
- Lack of Precision and Reliability: The system was prone to inaccuracies, and calibration results were often affected by noise and manual adjustments.

- Manual Operation: The process required manual tuning, making it operator-dependent and error-prone.

- Frequent Breakdowns: The system faced regular failures, and spare parts were often unavailable, causing delays.

- **Outdated Technology (!):** The system used outdated technologies that could no longer meet the precision requirements of the NICA project.

For the NICA project, approximately 8000 sensors needed calibration—5000 for the collider section and 3000 for the booster. These sensors were primarily ceramic-carbon (TVO) or CCS-type sensors, designed for high precision at cryogenic temperatures.
Calibration of such amount on the original calibration system, was not possible



3. The New System – A Polish Approach (NCU)

Solutions:

- **New technology (TI INA121 + Labjack U6 pro, AD DG303A)**

- **Automation**

Replaced manual operations with an automated calibration process to minimize human error and improve accuracy.
Introduced automatic switching between two current sources (10 µA for low temperatures, 100 µA for higher temperatures) for stable and precise temperature management.

- **Seebeck Effect Mitigation:**

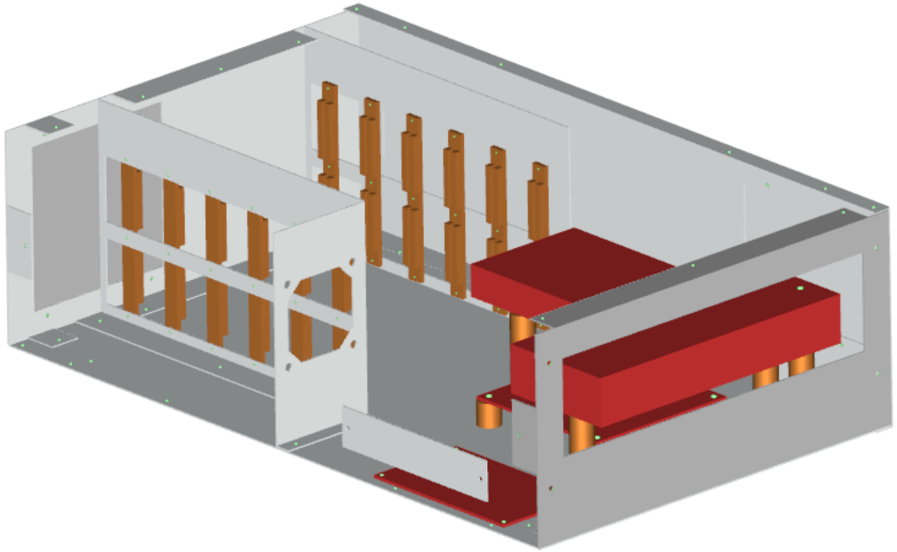
Automated polarity alternating.

- **Increased Scalability:**

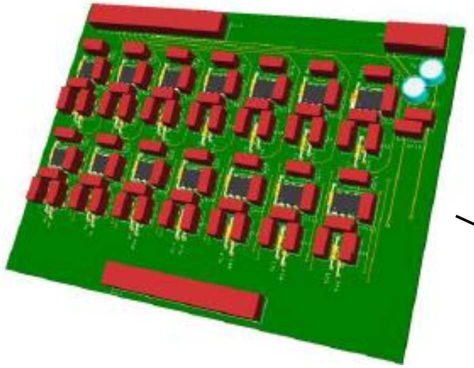
Designed the system to support calibration of up to 22 sensors, with potential for future expansions, improving system flexibility.

- **Improved Temperature Control:**

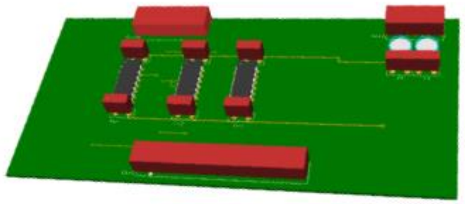
Manual heater replaced with a controller



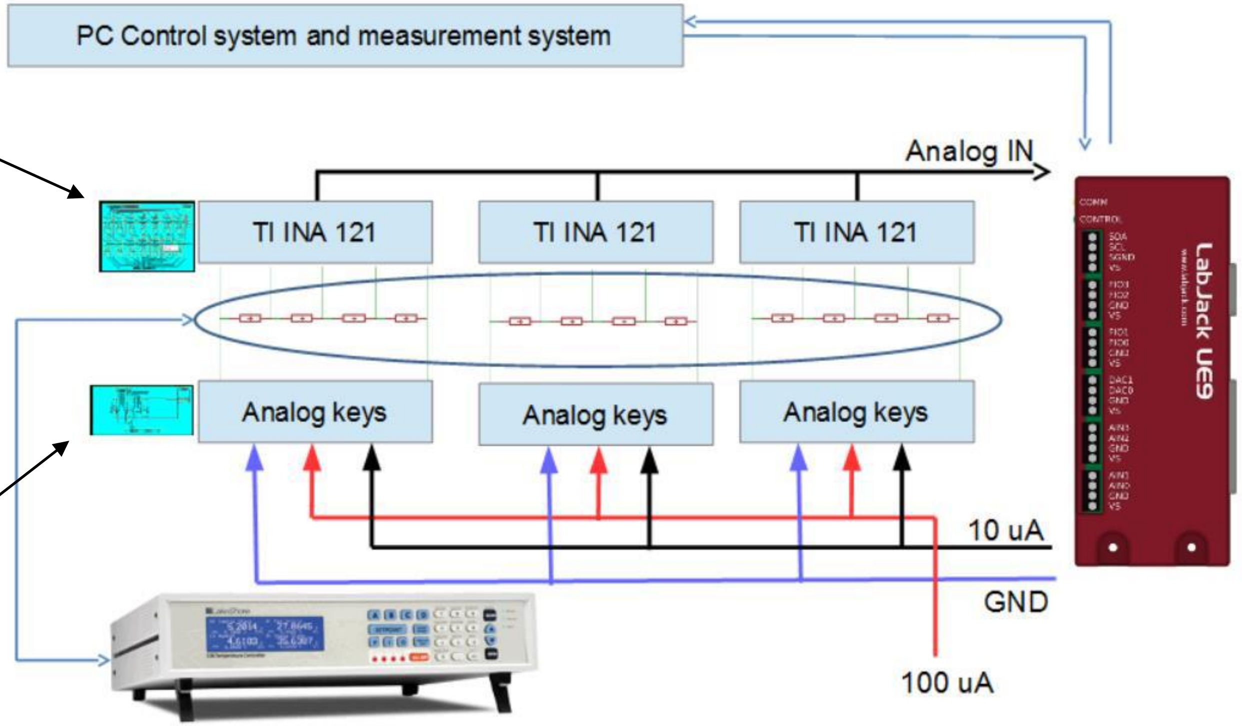
3. The New System – A Polish Approach (NCU)



Signal Conditioning boards
based on instrumental amplifier
(Texas Instruments INA 121)



Circuit switch boards
based on Analog Devices DG303
analog switches



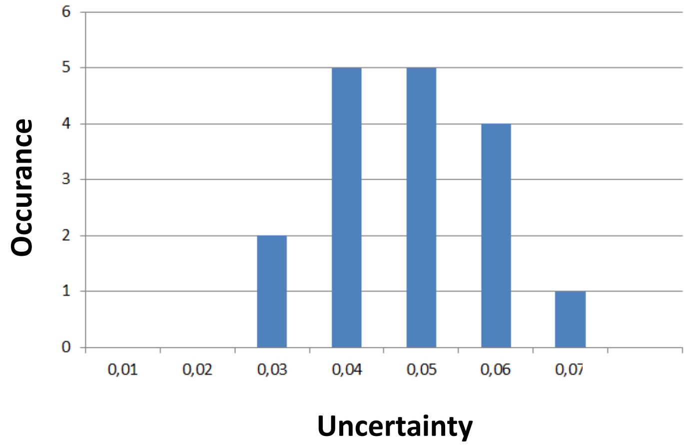
LabJack U6 PRO
DAQ system with 22 bit ADC

3. The New System – A Polish Approach (NCU)

NCU

Type A Uncertainty
Evaluated through statistical analysis as the standard deviation of repeated measurements. This represents the uncertainty due to variability in the data.

T [K]	294.7	77.00	4.2
σ [Ω]	0.042	0.072	0.304



$$\Delta R_x = |g_c \cdot \frac{R_r}{U_r} \Delta U_x| + |g_c \cdot \frac{U_x}{U_r} \Delta R_r| + |g_c \cdot \frac{U_x \cdot R_r}{U_r^2} \Delta U_r| + |\frac{U_x \cdot R_r}{U_r} \Delta g_c|$$

Type B Uncertainty
Calculated using the **method of total differential**. This accounts for uncertainty from non-statistical sources, such as calibration errors or sensor specifications.

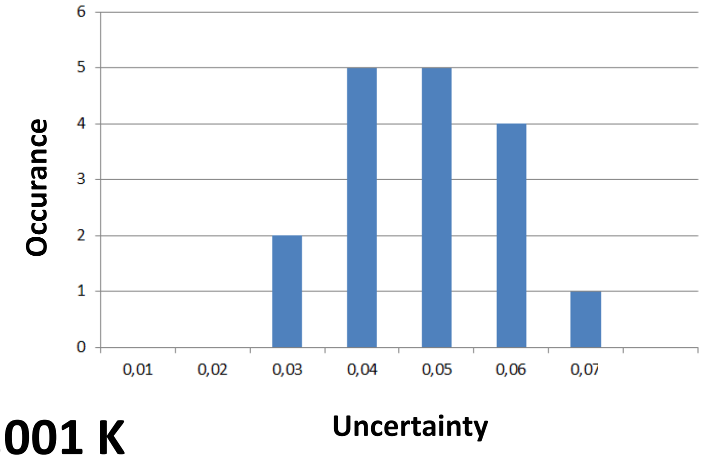
$T[K]$	294.7	77.00	4.2
$R[k\Omega]$	0.8	1.4	3
$I[\mu A]$	100	100	10
$\Delta R[\Omega]$	1.18	2.02	13.1
$\Delta R[\%]$	0.15	0.25	0.44

3. The New System – A Polish Approach (NCU)

Type A Uncertainty
Evaluated through statistical analysis as the standard deviation of repeated measurements. This represents the uncertainty due to variability in the data.

T [K]	294.7	77.00	4.2
σ [Ω]	0.042	0.072	0.304

≈ 0.001 K



$$\Delta R_x = |g_c \cdot \frac{R_r}{U_r} \Delta U_x| + |g_c \cdot \frac{U_x}{U_r} \Delta R_r| + |g_c \cdot \frac{U_x \cdot R_r}{U_r^2} \Delta U_r| + |\frac{U_x \cdot R_r}{U_r} \Delta g_c|$$

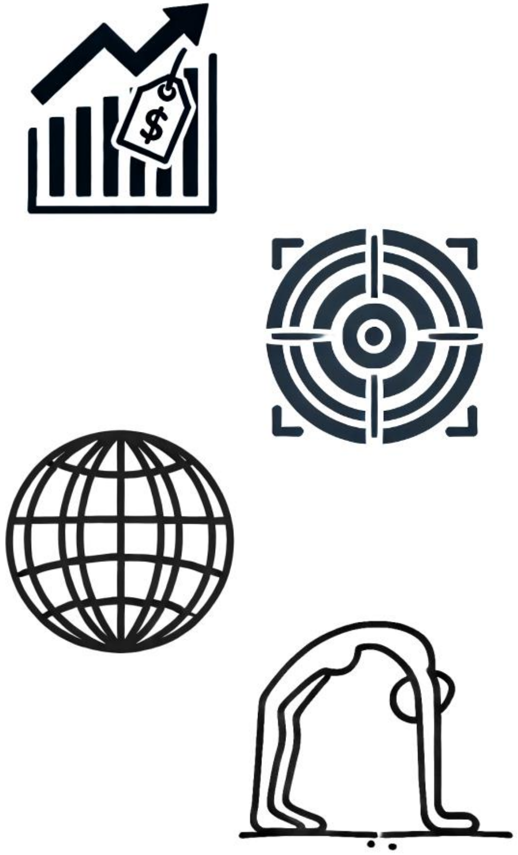
Type B Uncertainty
Calculated using the **method of total differential**. This accounts for uncertainty from non-statistical sources, such as calibration errors or sensor specifications.

$T[K]$	294.7	77.00	4.2
$R[k\Omega]$	0.8	1.4	3
$I[\mu A]$	100	100	10
$\Delta R[\Omega]$	1.18	2.02	13.1
$\Delta R[\%]$	0.15	0.25	0.44

≈ 0.025 K

4. Development of the System by Frako-Term

4. Development of the System by Frako-Term



Motivations:

- **Rising Costs of Commercial Solutions**

The prices of commercial calibration systems were increasing rapidly, making external options less viable and driving the need for an in-house solution to control costs.

- **Internal Demand for Precision**

Frako-Term required a highly reliable and flexible calibration system for its own projects and sensor measurements. Building a custom system ensured full control over performance and accuracy.

- **Geopolitical Constraints**

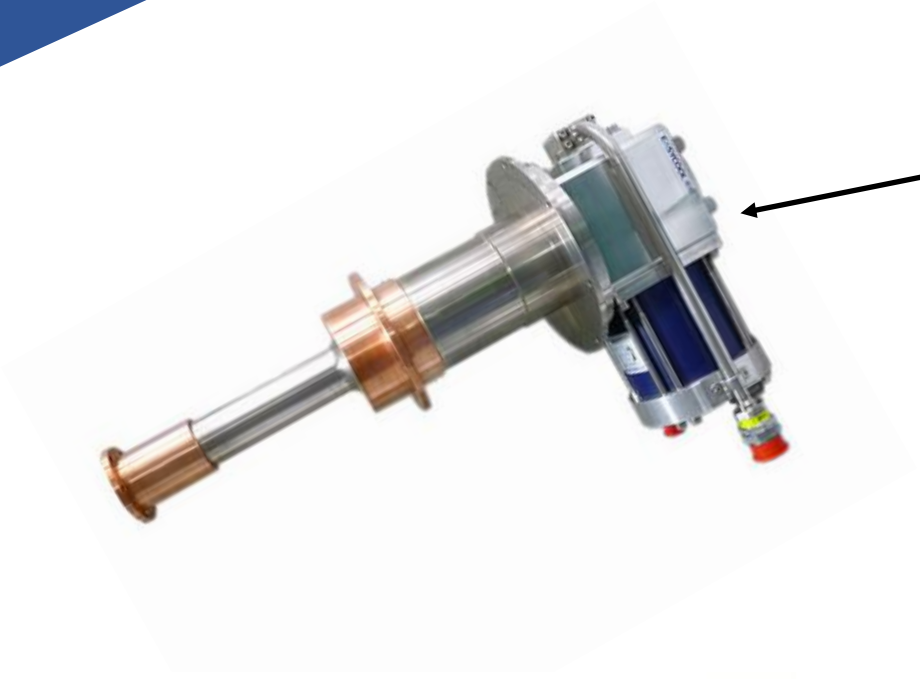
Relying on JINR in Dubna as a supplier was no longer feasible, prompting Frako-Term to develop a self-reliant solution to avoid disruptions.

- **Customization and Flexibility**

Frako-Term needed a system that could be tailored to meet diverse client needs.

4. Development of the System by Frako-Term

Challange: New Calibration Environment

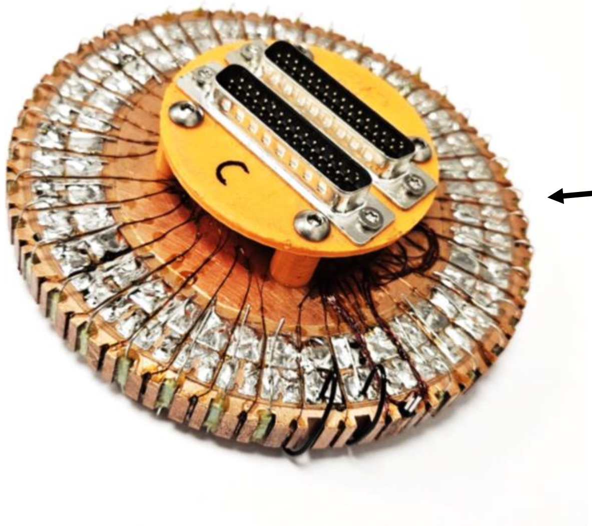


- Cryocooler Integration:

Instead of traditional liquid nitrogen or helium baths, the system now uses a cryocooler for controlled cooling. This allows operation at temperatures as low as **3.8K**, meeting the needs of the new environment.

- Vacuum Environment:

The system operates in a vacuum (**10^{-6} Torr**) to ensure proper thermal insulation, crucial for achieving such low cryogenic temperatures. Without this, it wouldn't be possible to maintain stable conditions at temperatures below 4K.



- Copper Measurement Head with:

The measurement head is made of copper and is insulated with Multi-Layer Insulation (MLI). This setup ensures better thermal stability, helping to maintain precision during the calibration process. The amount of channels was increased to 40.

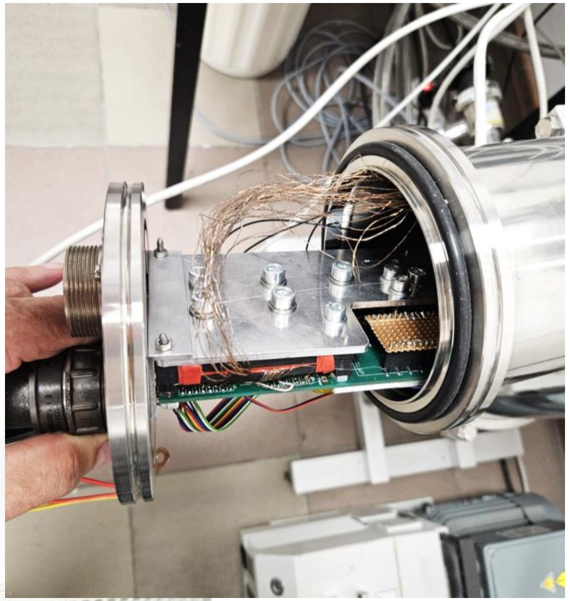
4. Upgrades

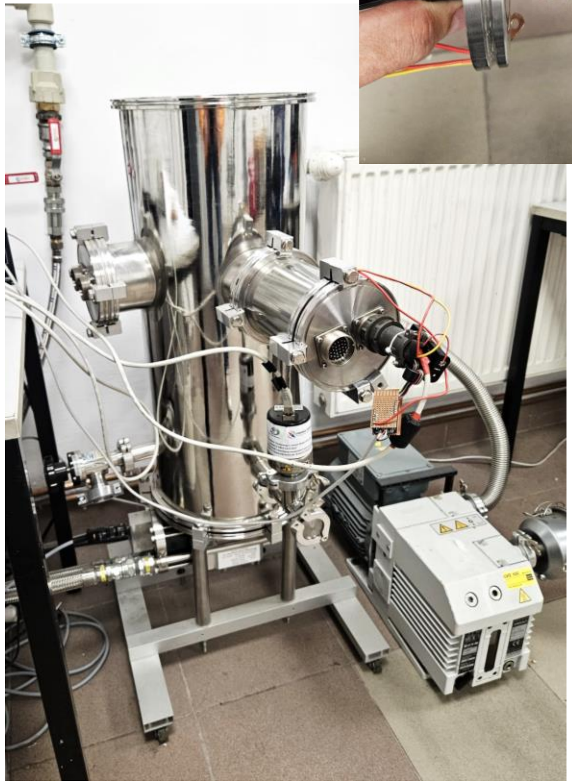
- Current Regulation System:

Instead of using two separate current sources as in the original Dubna system (10 µA for low temperatures and 100 µA for higher temperatures), Frako-Term introduced a constant voltage system that adjusts the current dynamically.

- Synchronous Readout:

The system employs simultaneous readout of 40 channels (38 sensor channels, 1 reference sensor, and 1 current measurement) using independent ADCs for each channel, ensuring high precision and real-time data collection.





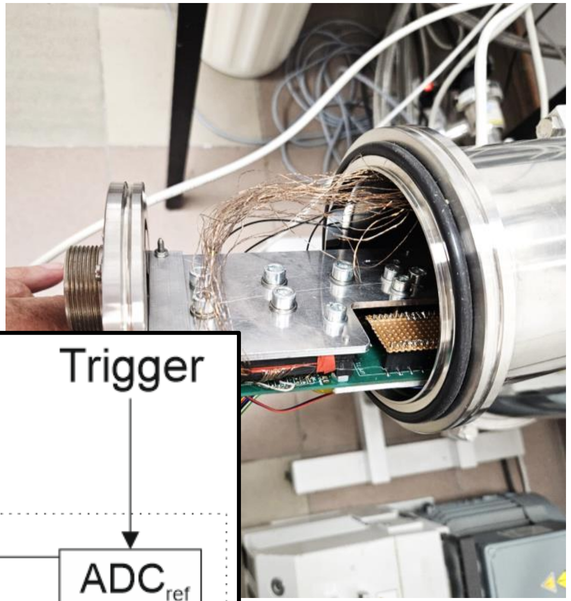
4. Upgrades

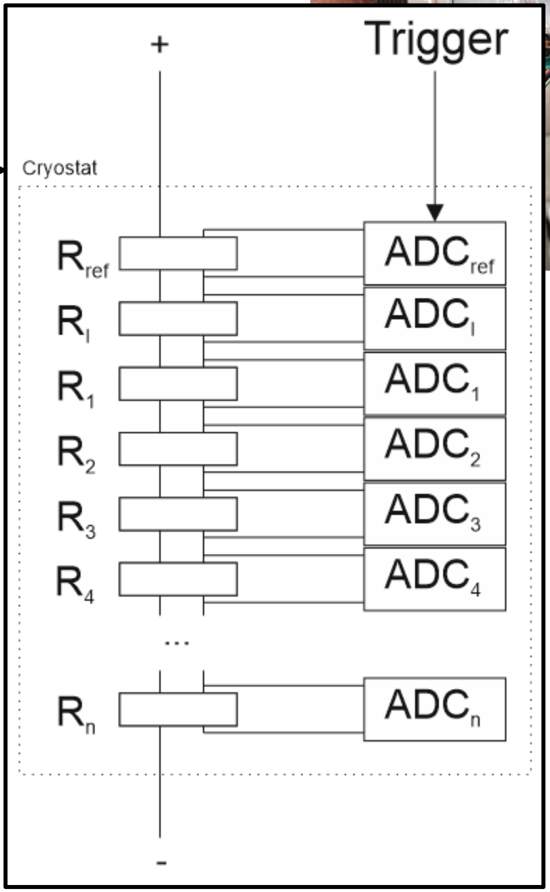
- Current Regulation System:

Instead of using two separate current sources as in the original Dubna system (10 µA for low temperatures and 100 µA for higher temperatures), Frako-Term introduced a constant voltage system that adjusts the current dynamically.

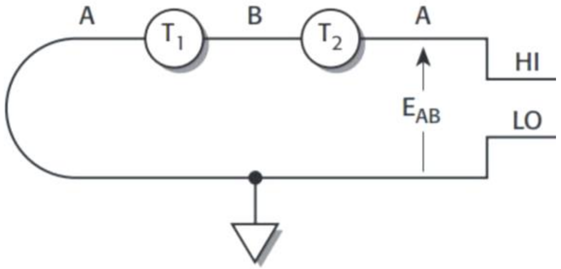
- Synchronous Readout:

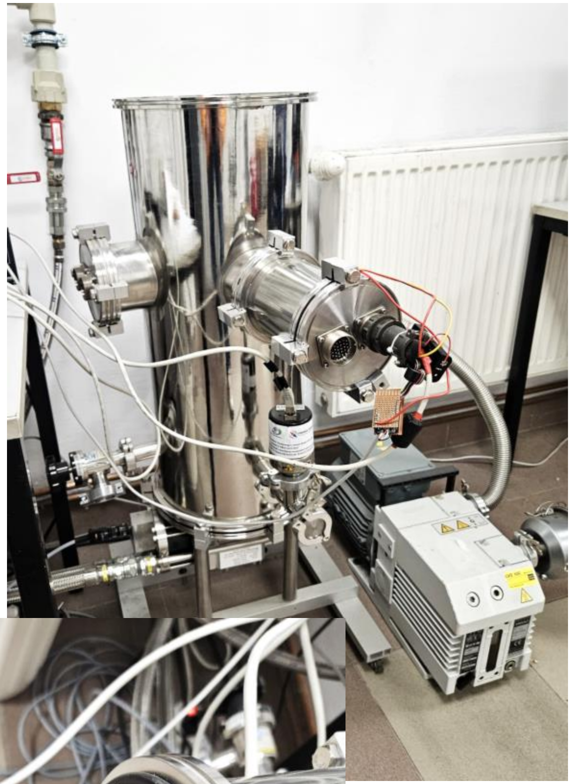
The system employs simultaneous readout of 40 channels (38 sensor channels, 1 reference sensor, and 1 current measurement) using independent ADCs for each channel, ensuring high precision and real-time data collection.

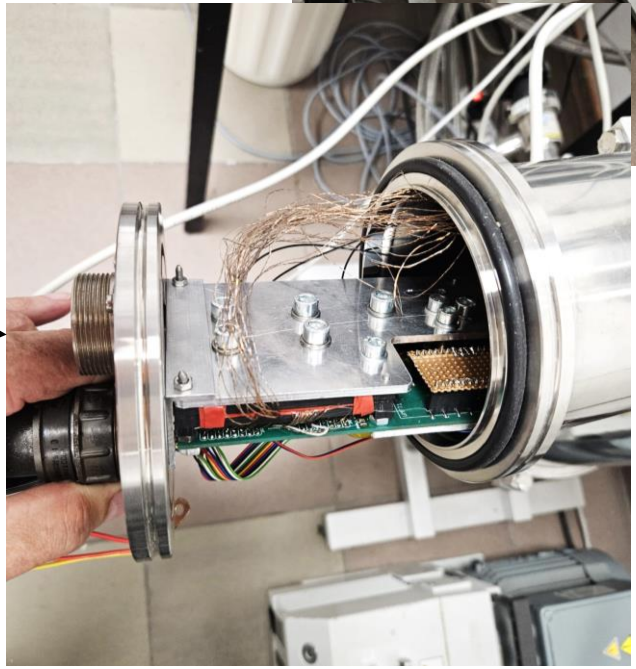




4. Upgrades







- Seebeck Effect Mitigation:

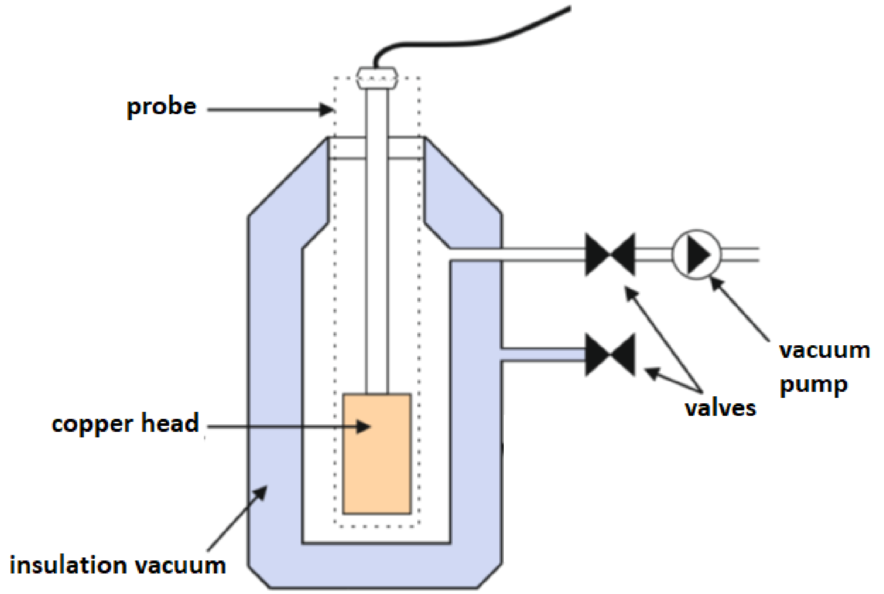
Frako-Term's solution also (like the NCU solution) uses electronics to minimize the Seebeck effect by alternating the direction of the voltage applied to the sensors during calibration.

This effect is further reduced, by moving the electronics to the cold side of the measurement enviorement.

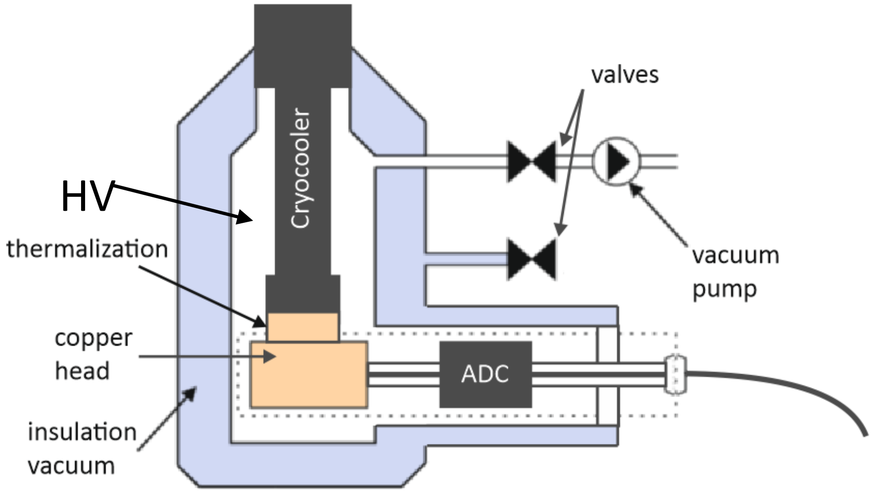
5. System comparison

	JINR/NCU System	Frako-Term
Cooling	Bath (helium, nitrogen)	Cryocooler
Automation	None/Full	Full
Sensor Calibration	20 pcs	38 pcs
Current regularion	2 sources	Dynamic
Vacuum Envioronment	Basic insulation vacuum	10^{-6} Torr
ADC placement	In warm	In cold
Sensor types	TVO	flexible

JINR



Frako-Term



Summary

1. The calibration system's journey began in the 1990s at JINR in Dubna, where early versions were designed for the nuclotron project but were limited by outdated technology and manual processes.

2. Around 2015, a new system was developed using modern technology but based on the original concepts. This system improved reliability, precision, and introduced partial automation.

3. Frako-Term took the system further, addressing the limitations of previous designs by:
   - Introducing cryocooler-based cooling to avoid helium dependance.
   - Creating a fully automated calibration process, reducing manual errors.
   - Expanding flexibility to handle up to 40 sensors, adaptable to various sensor types.

4. The system has undergone significant evolution over the years, and it continues to evolve as Frako-Term incorporates new technologies and innovations to meet future demands in cryogenic calibration.