US DoE-Topic # 29D: Low-cost, conformal, and efficient thermoelectric modules for on-detector electronics cooling

U.S. DEPARTMENT OF ENERGY
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Acknowledgement

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Overview

- Introduction to Nanohmics
- Technology background
- High-level vision for large-area, conformal TECs
- Program objectives
- Conformal TEC applications
- Summary

CONVERSION Materials
SENSING Technologies
MEASUREMENT Instrumentation

Electro-optics
Energy conversion
Biomolecular
Transducer materials
Computational Imaging
System integration

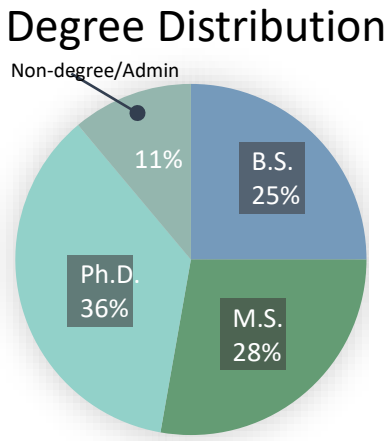
NANOHMICS

APPLIED SCIENCE

-Sensor/transducer materials
-Electromagnetic · Wavefront
-Molecular/Inks · Material interfaces
-Energy conversion · Heat/Emission
-Computational science/AI

INNOVATIVE ENGINEERING SYSTEM SOLUTIONS

-Microfabrication · Electronics
-Vacuum deposition · Coatings
-Embedded systems · Layout
-Sensors · Component integration
-Mechanical · Industrial design
-Thermal control · Electrodynamics
-Electro-optics · Electrical engineering
-Mechanical design · Control Systems
-Prototype · Low volume production
-Real-time computational imaging



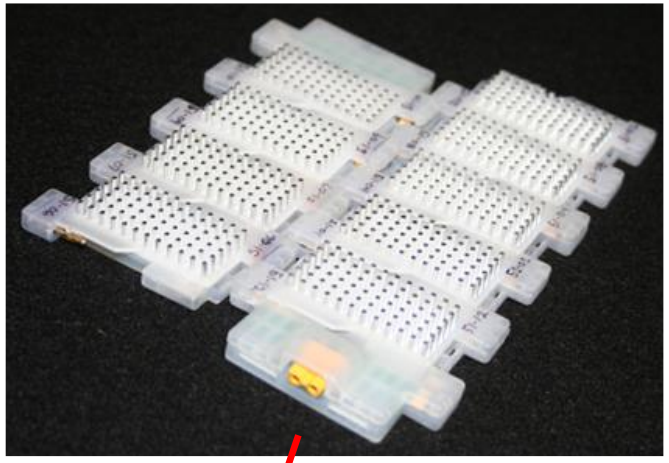
Founded: Austin, TX 2002
Staff: 46 technical

Facility: 13,500 sq.ft. industrial lab/flex
R&D: Industrial Sensors, Smart instrumentation

Nanohmics Company Capabilities

- Thermoelectric Devices
  - Cooling: current drives heat
  - Power Generation: temperature gradient generates current
- Capabilities
  - Materials fabrication and characterization
  - Device design and simulation
  - Thermoelectric device and systems fabrication and characterization
  - Cooling and power generation applications
- Products under development
  - Large-area and conformal TE cooling device (DoE)
  - Thermoelectrically-cooled Jacket (NAVY)
  - TEC Knee Therapy Wrap (IRAD)

Cooling Jacket application (NAVY)



DoE

TEC core technology

TEC wrap

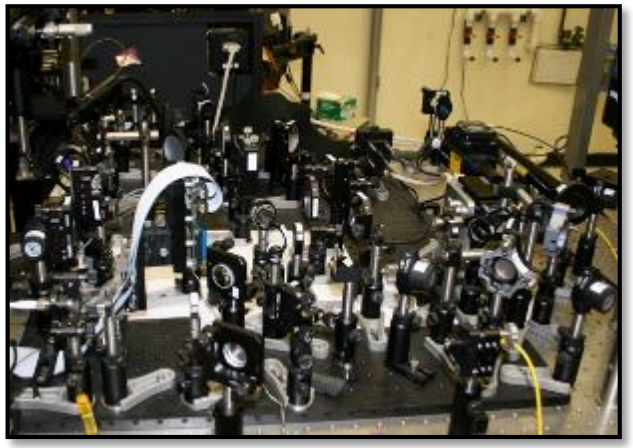
Cooling Therapy

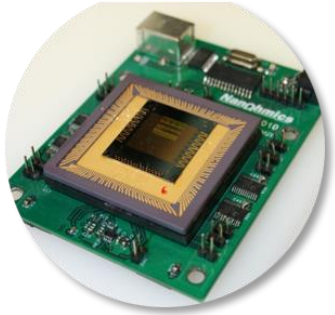
Conventional

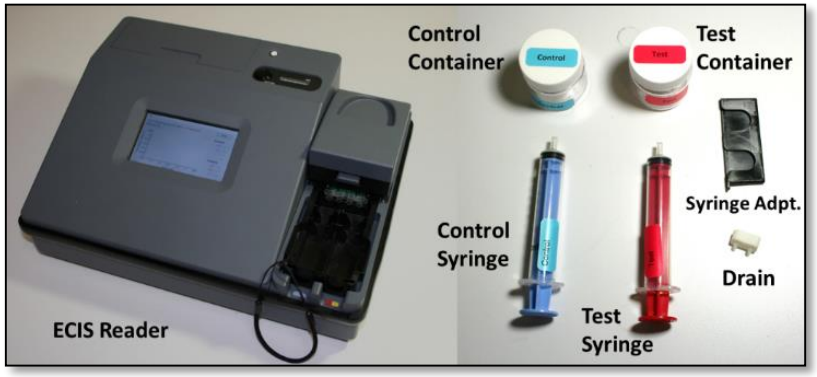
Nanohmics Company Capabilities

• Instrumentation Development

- Capabilities
  - Optical spectroscopy
  - Low-noise electronics
  - Digital signal/image processing
  - Real-time computational imaging
  - Precision measurements
  - Rapid full-custom prototyping
- Advanced products
  - Zowave™ passive wavefront correction (Several in field, LRIP w/ a prime)
  - ECIS™ water toxicity sensor (100+ units delivered and in use, active IDIQ)
  - GlideLine™ parachute navigation system (sold entire product division)





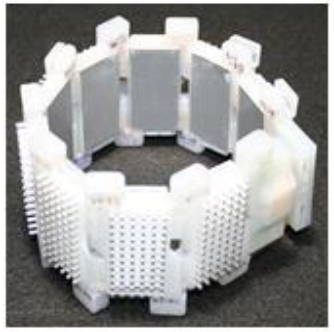


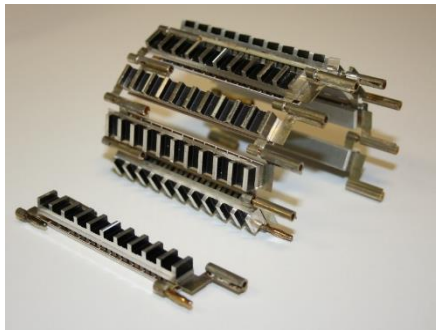
Program Overview

- **Program:** DoE-SBIR Phase-II program, 30 months (NCE)
- **Participants:** Nanohmics (lead), University of Virginia
- **Consultant:** Capstan Technology, Jefferson Lab
- **Program goals:**

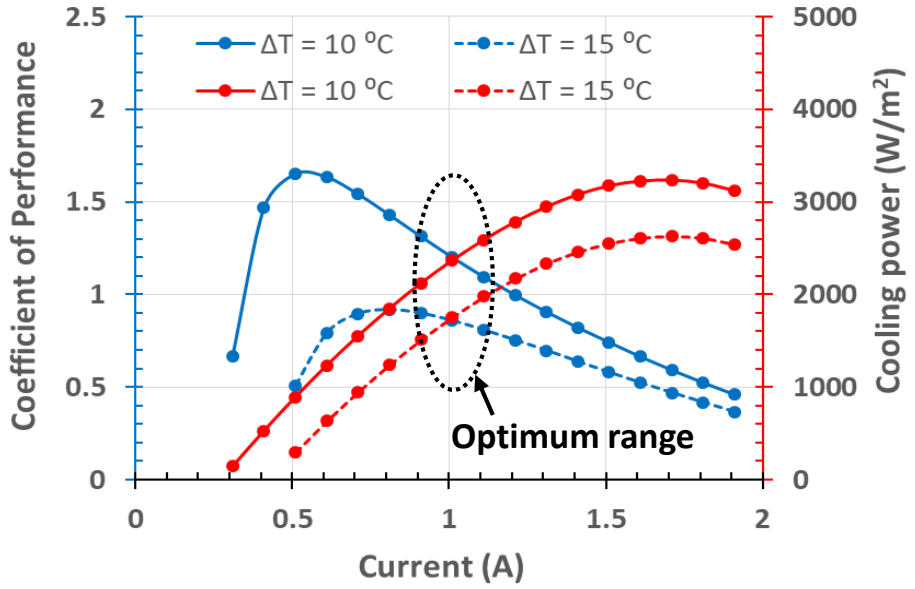
  Design and fabricate efficient, low-cost and conformal TEC systems for on-detector electronics cooling

  - Enhance COP of TEC
  - Fabricate 6″ x 18″ conformal TEC
  - Construct cooling system for on-detector electronics



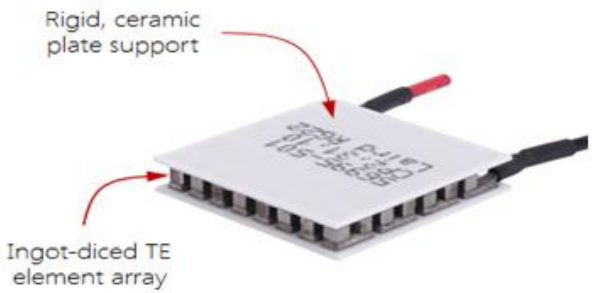


- Low-profile
- Large-area
- Conformal
- Low-Cost

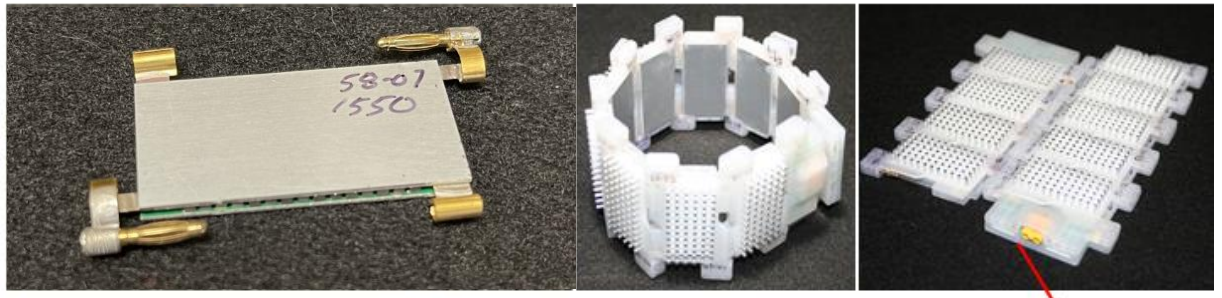


Concept Overview

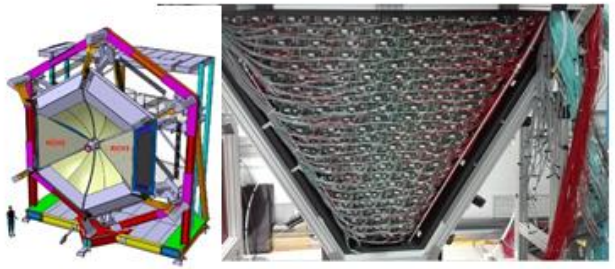
(A) Commercial thermoelectric cooler



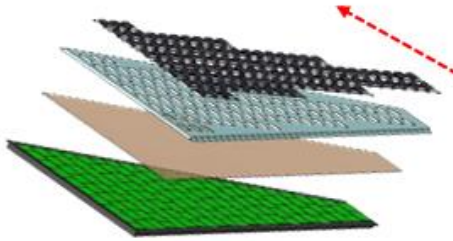
(B) Nanohmics' conformal thermoelectric cooler technology

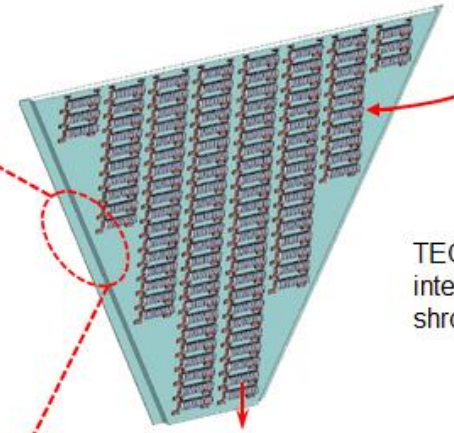


(C) Conformal TEC cooling system for RHIC on-detector electronics

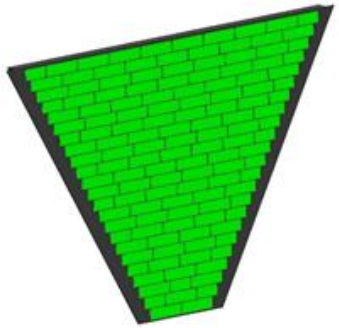


RICH detector and electronics

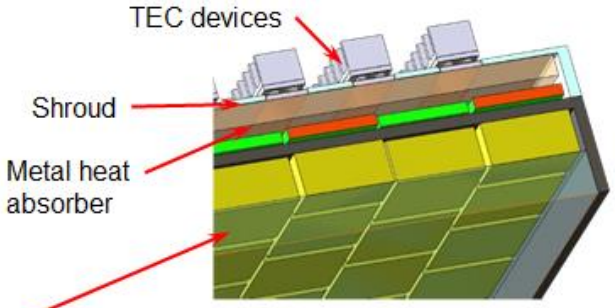


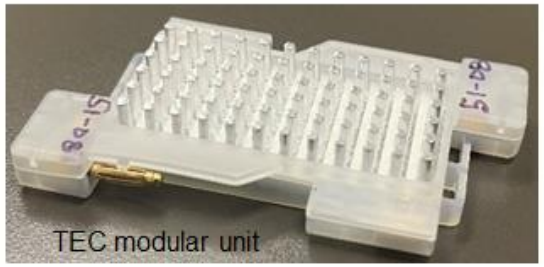


TEC integrated shroud



E-Panel PCBAs (Adapter, ASIC, FPGA)





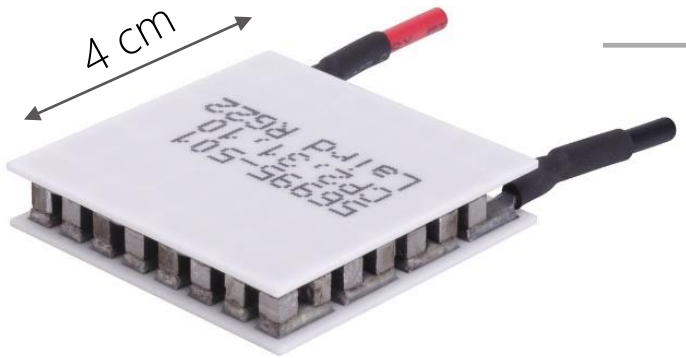
TEC modular unit

Technology Innovation:

Nanohmics designed and fabricated conformal TEC devices to cool on-detector electronics and maintain a temperature below 20 °C during Phase I

Limitations of Commercial Thermoelectric Coolers

- Thermoelectric (TE) devices are used in hundreds of cooling products
- TE devices have been manufactured the same way since the late 80s
- TE devices fabricated on ceramic plates are expensive (>$500/sq.ft. equivalent)
- Commercial TE devices require:
  - "tiling" and "fixturing" for large area cooling
  - application-specific connectivity and heat exchanger designs
  - application-specific system integration w/ controllers and power supplies



Commercial TE device

Food & beverage
Leader: Igloo
Cost: $150-400

Enclosure cooling
Leader: Grainger
Cost: $700-3500

Biotech/Medical
Leader: Thermo Fisher
Cost: $3000-15000

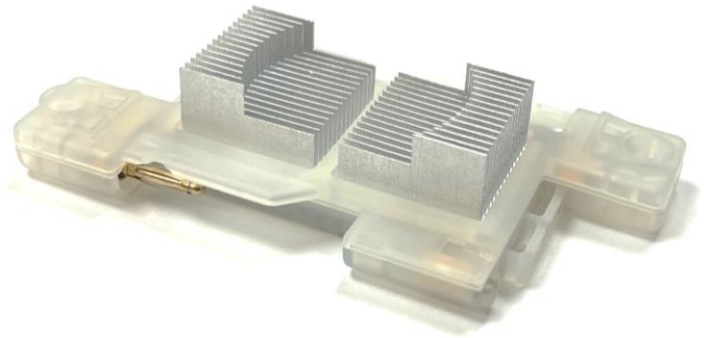
Consumer (*e.g.* auto)
Leader: Gentherm
Cost: $300-500

Therapeutics
Leader: Hyperice
Cost: $500-700

Wearable cooling
Leader: Sony
Cost: $150-250

Technology Innovation: Modular Thermoelectric System - Thermolynx

- Modularity provides large-area, high-efficiency thermal management solutions as required for on-detector electronics cooling
- ΔT =71°C measured at $T_{ambient}$ = 25°C, higher compared to Commercial TE
- CoP >2 with cooling power > 0.75 W/cm^2 ($T_{ambient}$ = 25°C, ΔT=10°C)- **Milestone achieved**
- Conformable and compliant for high thermal interface contact
- Adaptable sizing and flexibility meets new application requirements
- Designed for rapid prototyping w/ integrated heat exchangers
- Low-profile is configured for wearable/textile comfort
- Low-cost manufacturing process ($199/sq.ft.)



Module weight – 20 g

ThermoLynx-Powered Commercial Applications

Entry Products

- –Wearable **PPE** (**welding, first responders, soldiers, clean room**)
- –Wearable **medical** (ambulatory cold therapy, cast-integration)
- –**Cold chain/fixture thermal management**
- –**Enclosure air conditioning (wall/appliance-mounted)**
- –Portable **and battery-powered food & beverage**
- –**Scientific and biotech thermal cycling/precision thermal control**
- –**Consumer comfort cooling**

Modular TE provides large-area, high thermal interface contact, programmable cold management

PPE environment cooling

EV battery management

5G era comm cooling

Therapeutic/medical wearables

Phase II Technical Objectives

Technical Objective 1: Design and fabrication of high-ZT thermoelectric modules

Technical Objective 2: Performance demonstration of fully-operational modular assemblies (TE alpha prototype)

Technical Objective 3: Design and proof-of-concept demonstration of a modular TE system for on-detector electronics cooling

Phase II program work plan

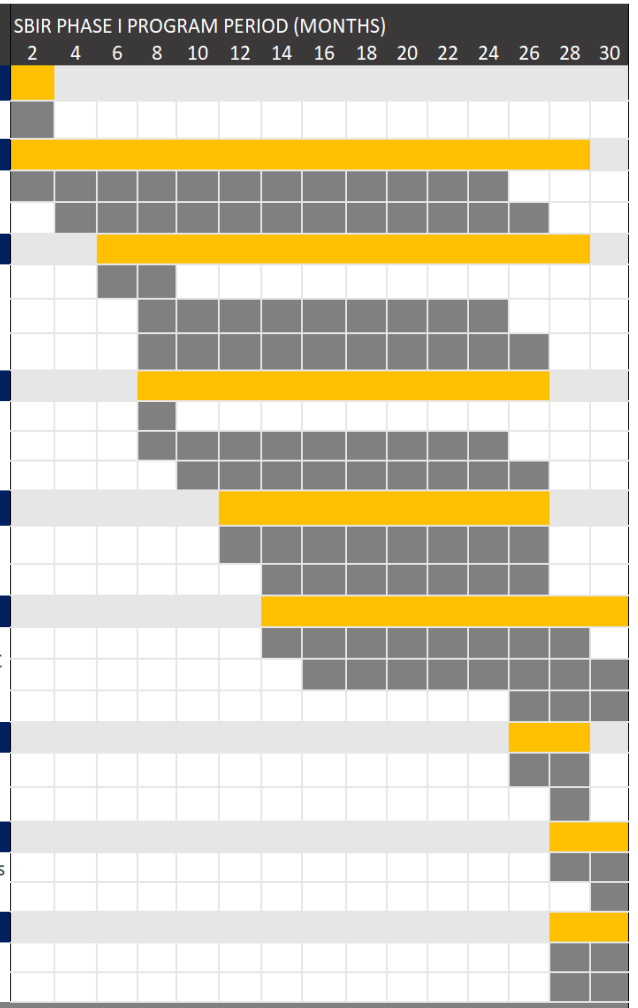
Program Objective: Low-cost, efficient and conformal TEC fabrication with CoP>1.5 for ΔT~10°C cooling of on-detector electronics

Impact: Enable detector to maintain a temperature below 20 – 25 °C

Phase II goal: Demonstrate cooling performance of a 6″ x 18″ conformal TEC prototype device and cooling system for detector's electronics

Team capabilities: Extensive TEC design, fabrication, and commercialization experience. Flexible/stretchable medical sensor technology development experience.

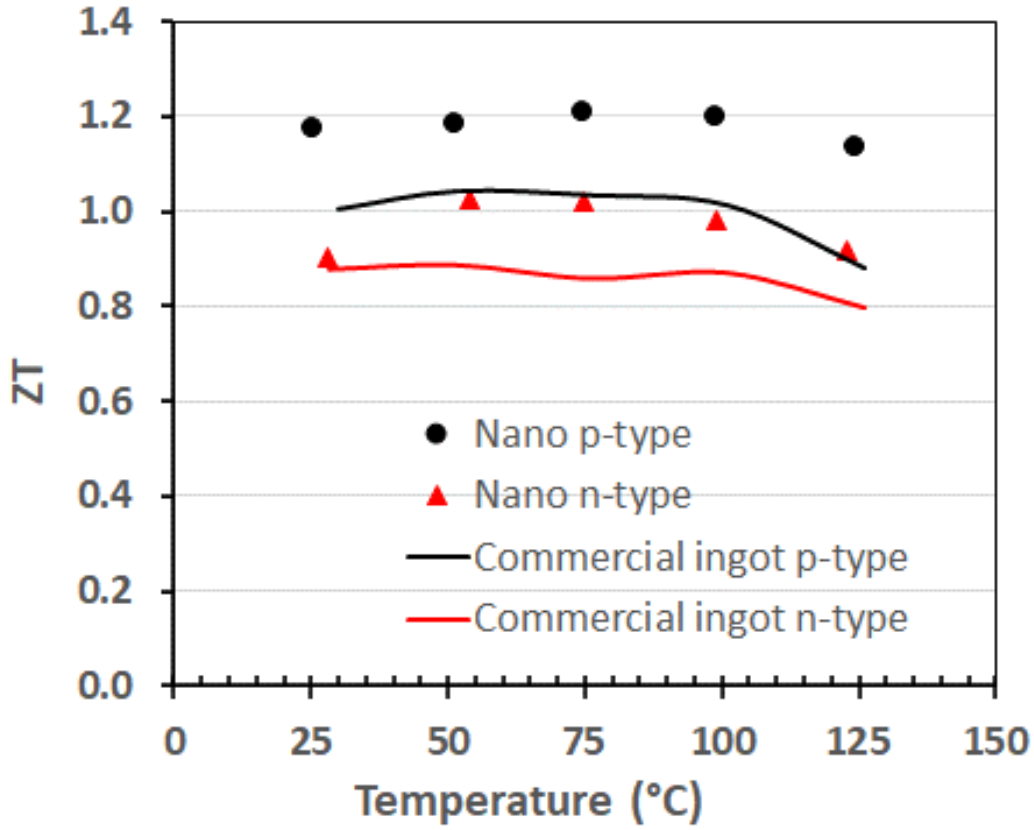
TECHNICAL OBJECTIVE Work Plan Tasks	Milestone
1 Program kick-off with sponsor	
Establish, analyze, and document system requiremnts	Kick-off meeting; specification slides
2 Optimization of high-ZT thermoelectric materials	
Synthesize TE materilas	Fix TE compositions of p- and n-type with ZT around 1.0
Optimize TE composition and process	
3 TE consolidation across fiberglass and electrode development	
Consolidate TE materials across fiberglass	6" wide metallized TE element array across fiberglass with ZT around 1.0 and contact resistance < 10 μΩ-cm^2
Develop contact materials	
Characterize and optimize metallization layer	
4 Concept demonstration unit developments and optimization	
Optimize dielectric and thermal spreader materials	Fabrication of 6" wide row module with cooling performance demonstration
Design and assemble TEC unit	
Characterize the CDU unit	
5 Heat exchanger design and component fabrication	
Design and simulate hot side heat exchangers	Fabrication of optimized heat exchanger for TEC hot side
Fabricate mechanical components	
6 Fabrication of alpha-prototype conformal TEC System	
Design and fabricate alpha-prototype TEC	Fabrication of 6" x 18" conformal TEC system
Optimize materials and components	
Design and fabricate electrical components	
7 Alpha unit performance demonstartion	
Characterize alpha-prototype TEC	Full third party validated alpha-prototype cooling performance
Validate performance by third party	
8 Beta design of on-detector electronics TEC cooling system	
Design on-detector electronics TEC cooling system	Fabrication of on-detector electronics TEC cooling system
Optimize materilas and components	
9 Volume manufacturing process design	
Design TEC volume manufacturing components	Detail low-cost roll process TEC manufacturing plan
Optimize TEC roll manufacturing for low-cost production	



Phase II deliverable: Phase II final report, fully characterized 6" x 18" conformal TEC system, manufacturing design documentation

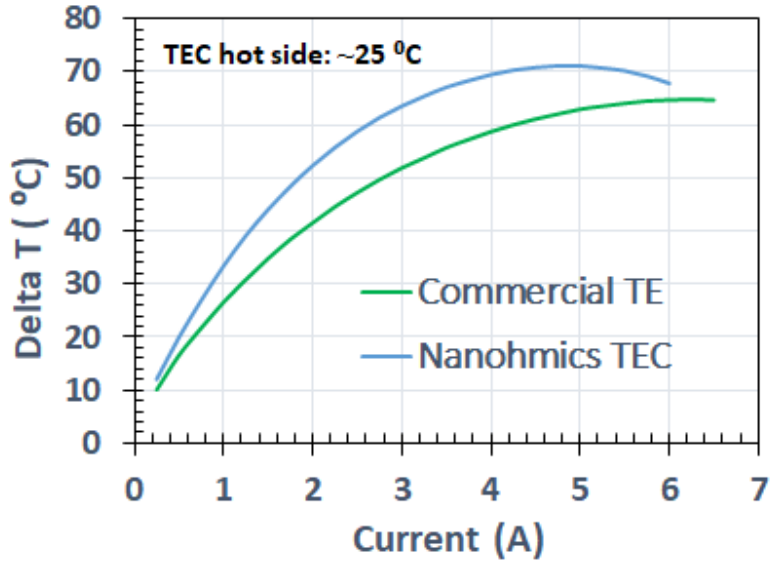
High-performance thermoelectric materials

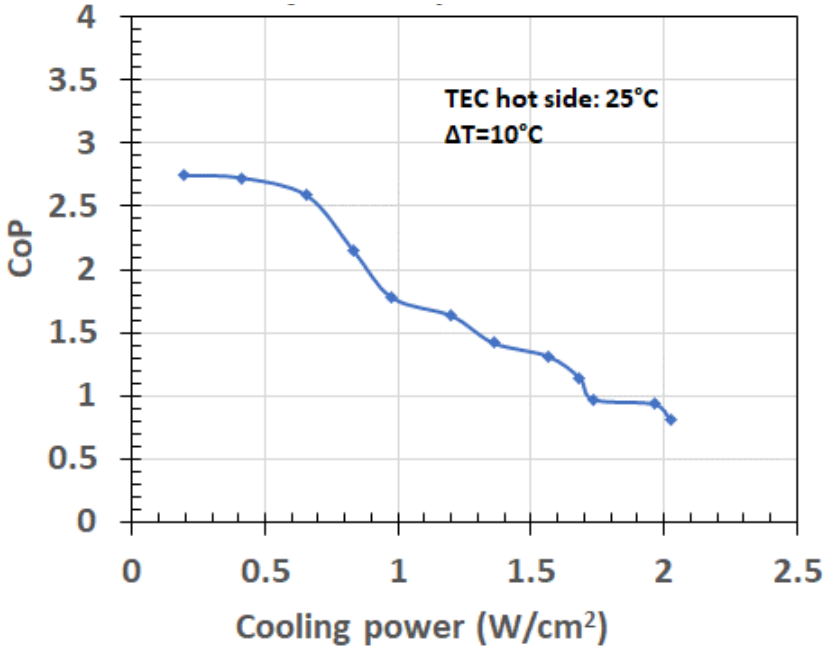
- High performed TE materials synthesis
- Base compositions: $Bi_{0.5}Sb_{1.5}Te_3$ (p-type), $Bi_2Te_{2.7}Se_{0.3}$ (n-type)
- Room temperature figure of merit (ZT): 1.2 (p-type), 0.9 (n-type)
- Better TE materials compared to commercial TE
- CoP proportional to ZT
- Targeted CoP ~ 2.0 with ΔT = 10 °C



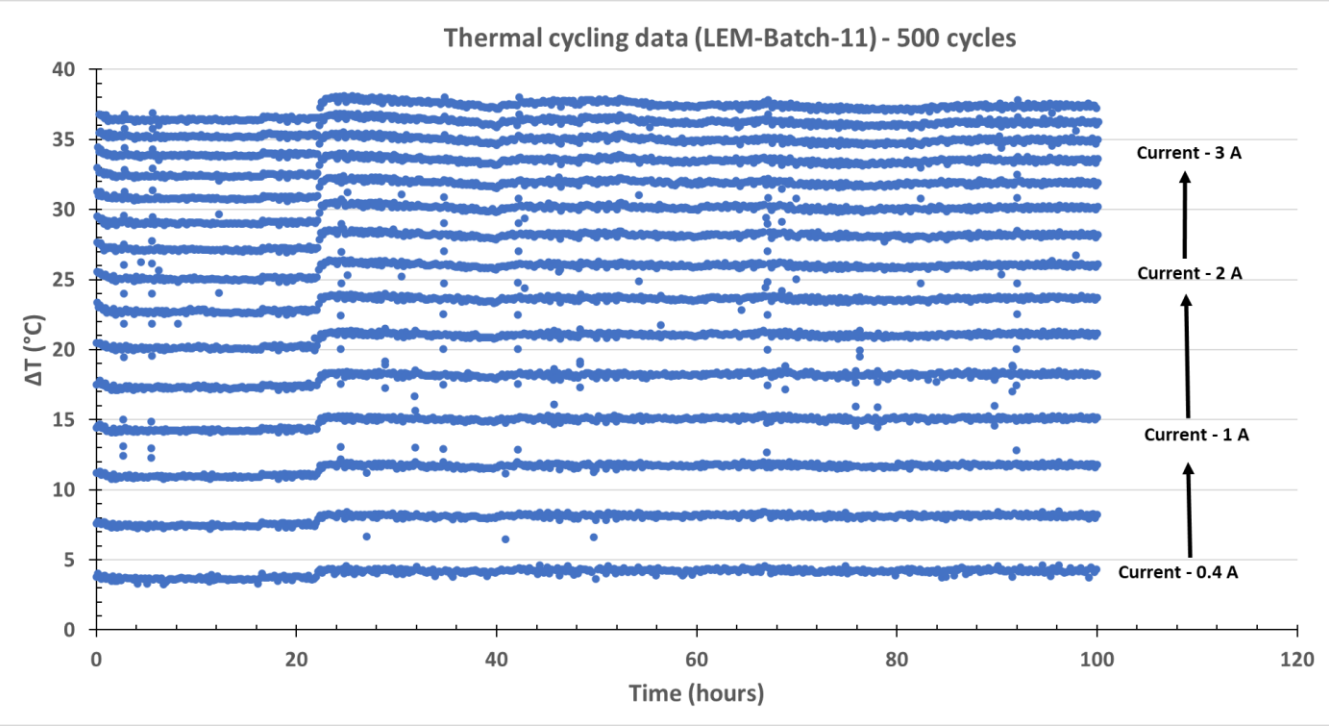
Cooling performance of *Thermolynx* modules

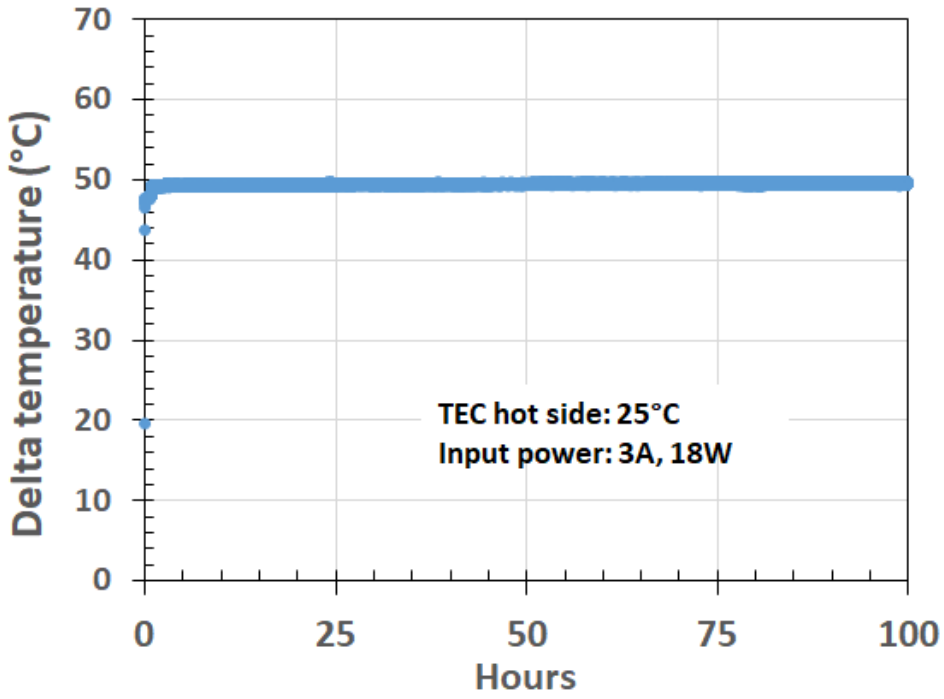
- 20mm x 41mm TEC
- CoP and cooling performance measured at ΔT = 10°C and T_{hot} = 25°C
- ΔT =71°C measured at $T_{ambient}$ = 25°C, higher compared to Commercial TE
- CoP >2 with cooling power > 0.75 W/cm^2
- Targeted cooling performance for room temp cooling applications such as on-detector electronics





Thermal stability data





- Thermolynx modules show robust mechanical and thermal stability for 500 cycles and 100 hours of continuous operation

Summary

- Nanohmics has developed low-cost, conformal, and efficient thermoelectric cooling modules (Thermolynx devices)
- Thermolynx devices are based on PCB substrates, and assembled using automatic and tape & reel-based manufacturing processes
- The Thermolynx devices are modular in structure, and amenable to a large-area cooling system using stretchable and mechanically-complaint electrical connectors
- A CoP ~ 2.0 and cooling power > 0.75 W/cm^2 measured for room temperature cooling applications (T_{hot} ~ 25 °C, ΔT= 10 °C) such as on-detector electronics cooling
- Thermolynx are robust, thermally-stable, and easily integrable into cooling systems
- **Nanohmics' devices are ready to build the detector cooling system as well as any other cooling applications, any collaboration is welcome!**

Thank You!.....Questions??