

Magneto-Thermoelectrics in Cryogenic, Room, and High-Temperature Regimes

MATERIAL AND DEVICE INNOVATIONS

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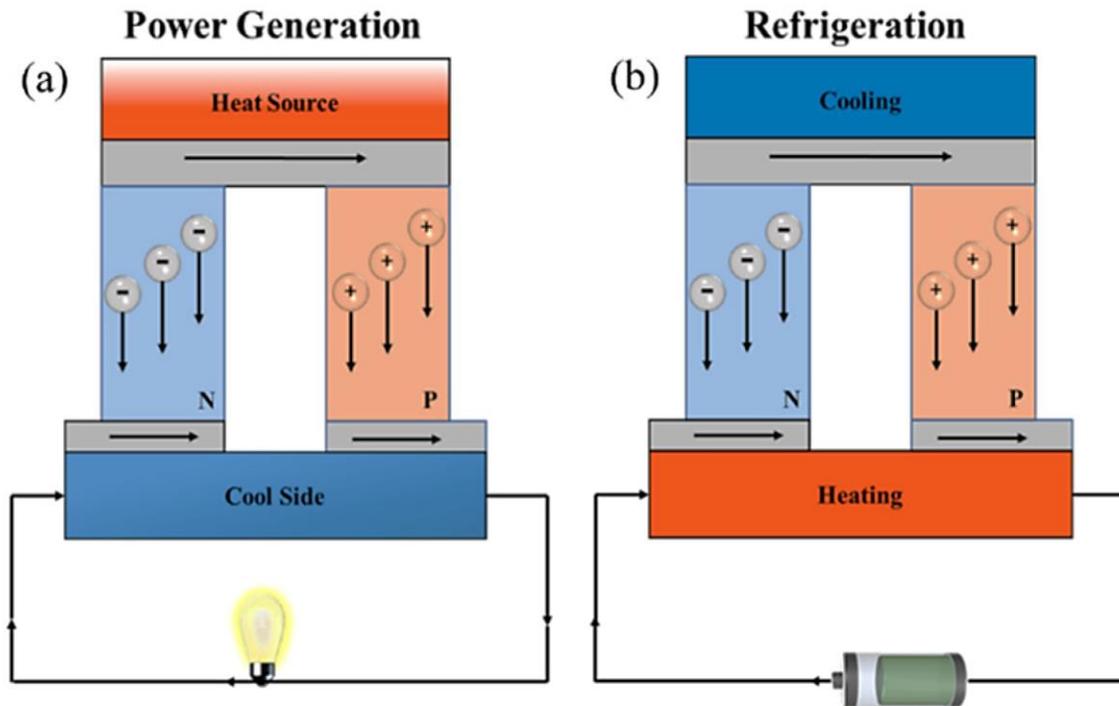
1 Why thermoelectrics?

- thermoelectric effect (TE):

$$ZT = \frac{S^2 \sigma T}{\kappa}$$

SEEBECK EFFECT

$$\Delta T \rightarrow \Delta V$$



PELTIER EFFECT

$$\Delta V \rightarrow \Delta T$$

[Huo B. and Guo C. Y., *Molecules* 2022]

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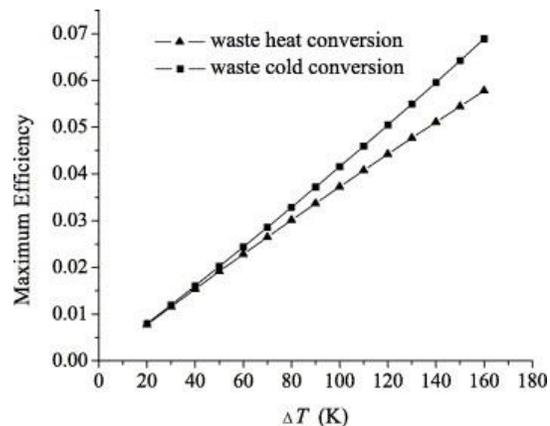
$$\Delta V \rightarrow \Delta T$$

- potential applications - environmentally-friendly, no mechanically moving parts, no emissions

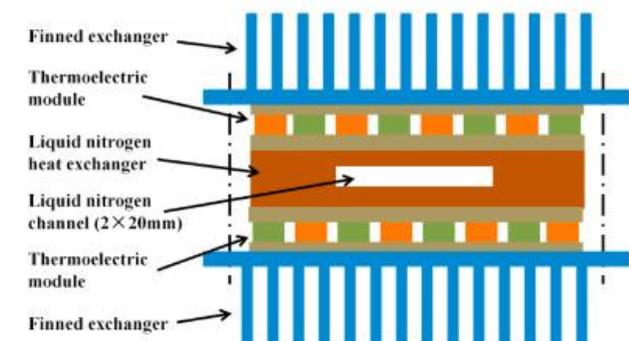
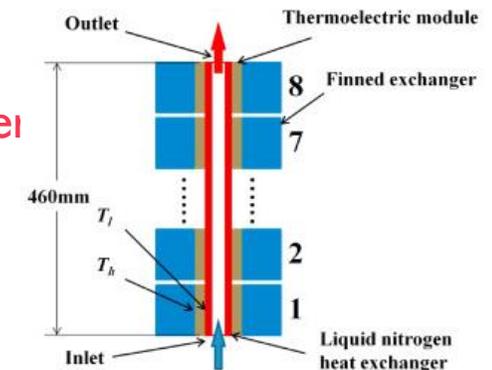
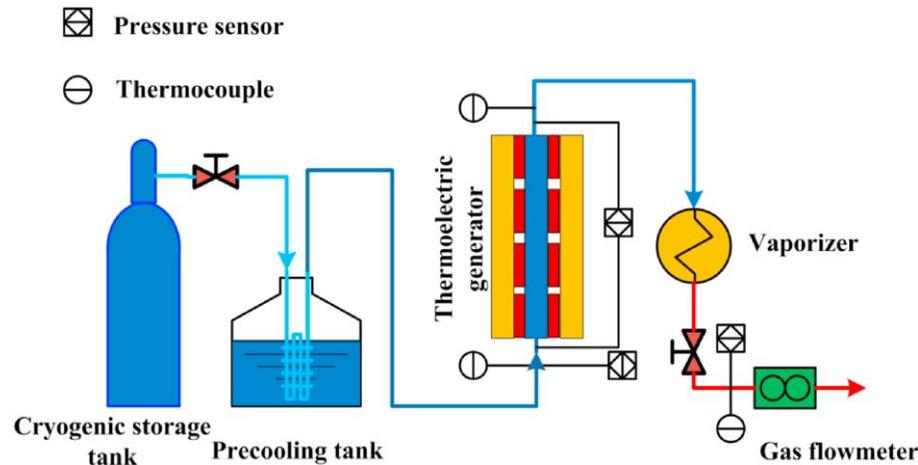
- waste heat recovery by energy harvesting

→ HIGH – ROOM TEMP.: automobile exhaust, industrial waste excess heating power

→ CRYO. – ROOM TEMP.: cryo-medium (LN2, LNG) excess cooling power



[Sun et al., Energy Conversion and Management 2005]



Cross-section diagram

[Ge et al., Energy 2021]

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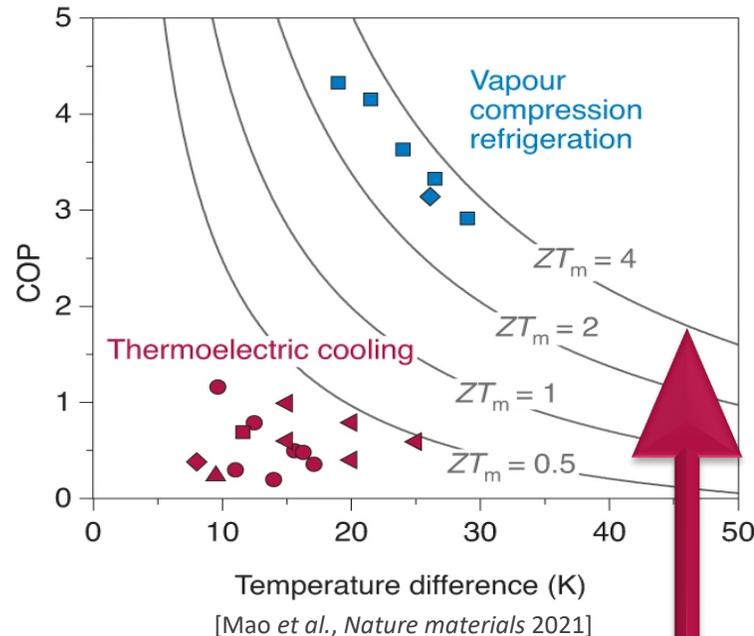
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- *potential applications* - environmentally-friendly, no mechanically moving parts, no emissions
 - waste heat recovery by energy harvesting
 - HIGH – ROOM TEMP.: automobile exhaust, industrial waste excess heating power
 - CRYO. – ROOM TEMP.: cryo-medium (LN2, LNG) excess cooling power
 - solid-state cooling – electrical (adaptive) control
 - electronic systems, laser diodes, infrared detectors, superconducting systems and quantum qubits
 - solid-state thermal management
 - TE thermal switches: adaptive thermal control
 - TE thermal diodes: enhanced heat flow in one direction by using TE materials with different ZT s

1 Why thermoelectrics?

- *benefits*: lightweight, small, inexpensive
- *challenges*: TE material selection, optimal device performance

difficult to obtain high ZT !



$$ZT = \frac{S^2 \sigma T}{\kappa} - \text{parameters are interlinked!}$$

$$\kappa \approx \kappa_{latt.} + \kappa_{el.}$$

Minimize by enhancing phonon scattering?
(point defects, dislocations, nanostructures, multiscale defect structures)

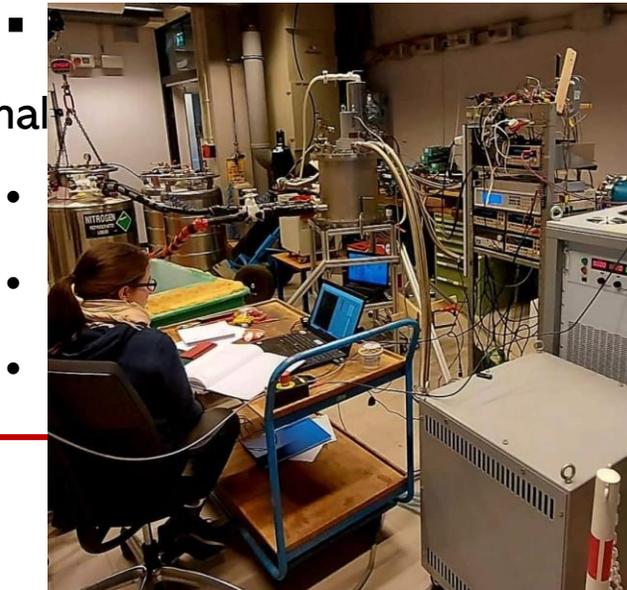
✗ DOESN'T WORK FOR CRYOGENICS!

MAGNETIC-FIELD ENHANCEMENT!

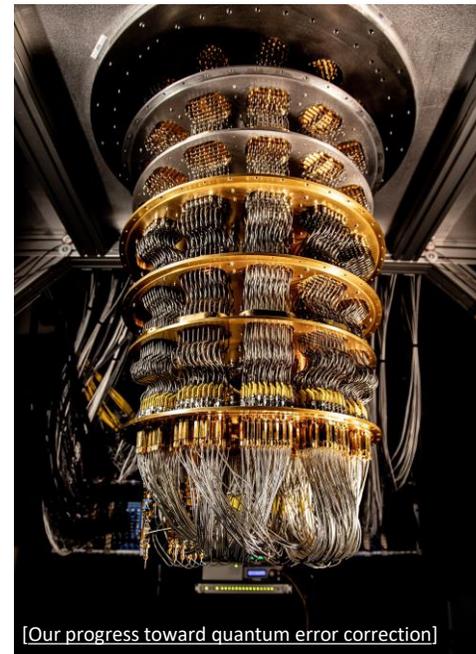
1 Why magneto-thermoelectrics?

- enhancing thermoelectric effect by applying external magnetic fields
- potential applications:
 - (adaptive) cryogenic cooling

• chal



MTE

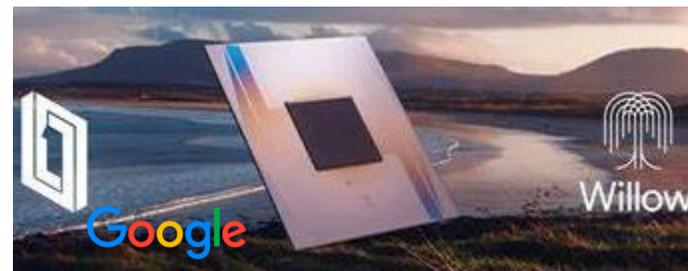


[Our progress toward quantum error correction]

[D. Gačnik, *personal archive*, Airbus UpNext's ASCEND – Advanced Superconducting and Cryogenic Experimental powertrain Demonstrator]



H2FLY - Realizes hydrogen-powered zero-emission aviation.



2 Magneto-thermoelectrics device

- **DEVICE-LEVEL OPTIMIZATION:**

- operational temperature: cryogenic, room-, and high-temperature regimes

- **MAGNET** type:

- low-T & high-T superconductors
- permanent ferromagnets
- (electromagnets)

TEMPERATURE-DEPENDENT!

- **MTE** material:

- optimized Seebeck coefficient S – max. voltage output
- optimized ZT – max. efficiency
- optimized S and ZT – best MTE performance!

TEMPERATURE-DEPENDENT!

- **thermal management:** magnet-induced, resistive (Joule), and parasitic heat losses

TEMPERATURE-DEPENDENT!

- **manufacturability:** balancing rare earth material costs

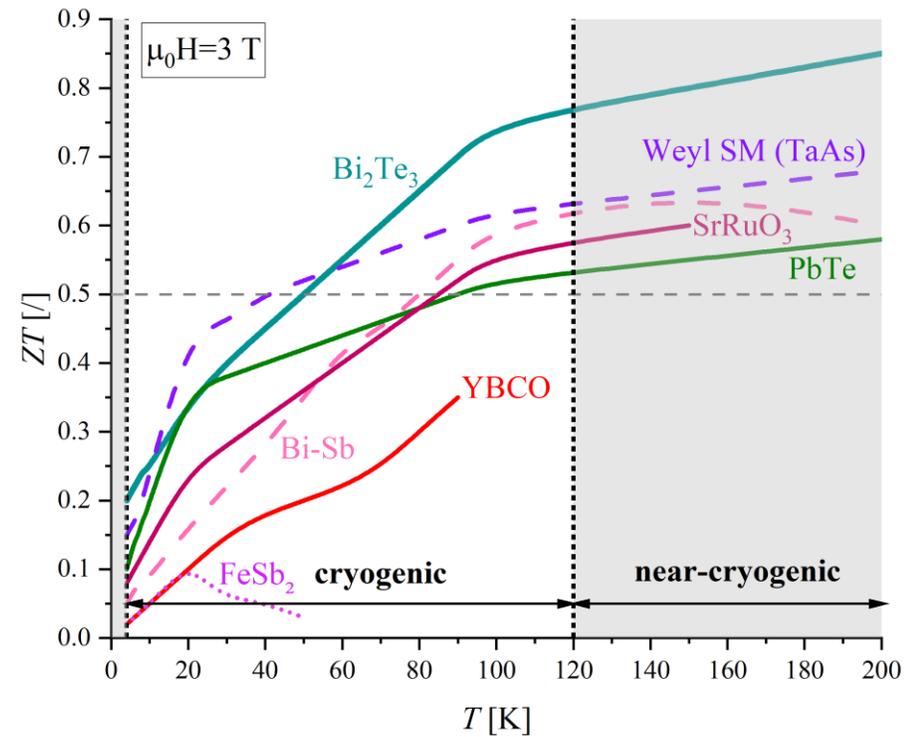
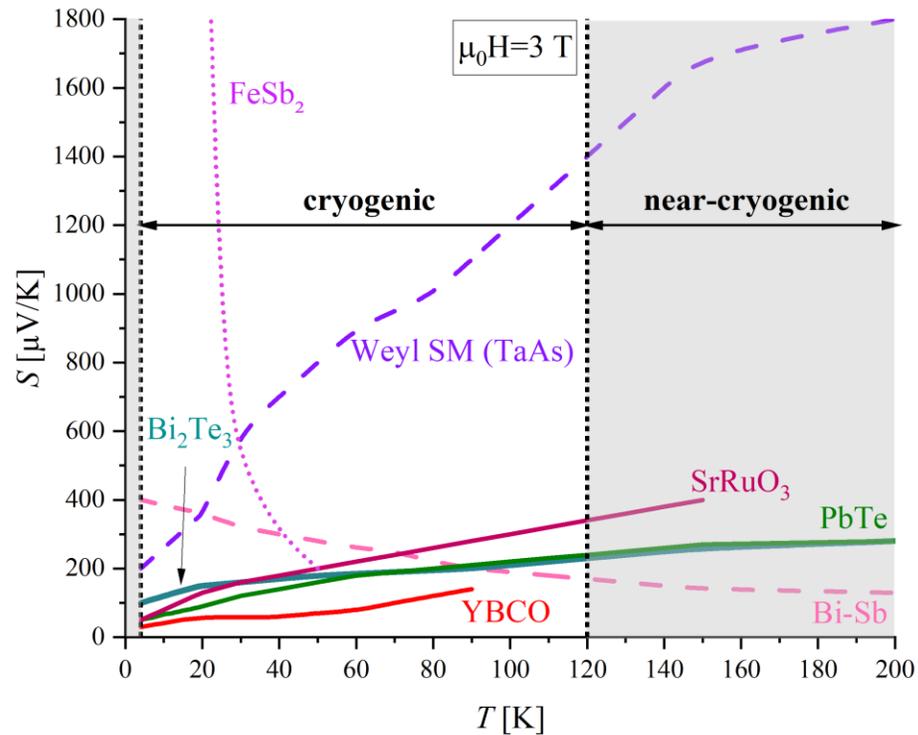
3 *Cryogenic magneto-thermoelectrics*

- MAGNET type:
 - ~ 2 T up to 25 K: low-T superconducting magnets – 4 K: up to 25 T, 20 K: up to 6 T
 - ~ 2 T up to 90 K: high-T superconducting magnets – 4 K: up to 100 T, 20 K: up to 50 T
 - ~1.4 - 2 T in all cryogenic regime: permanent magnets ($\text{Nd}_2\text{Fe}_{14}\text{B}$, SmCo)

- MTE material:
 - 10 – 100 K: Bi & Bi-Sb Alloys
 - under 5-9 T (anisotropic Fermi surface)
 - 90 – 110 K: high-Tc superconductors ($\text{YBa}_2\text{Cu}_3\text{O}_7$, Bi-2223)
 - under 3-8 T (vortex movement in the vortex-liquid phase)
 - 150 – 300 K: topological insulators (Bi_2Te_3 , Sb_2Te_3)
 - under 1-3 T (spin-momentum-locked surface-state disruption)

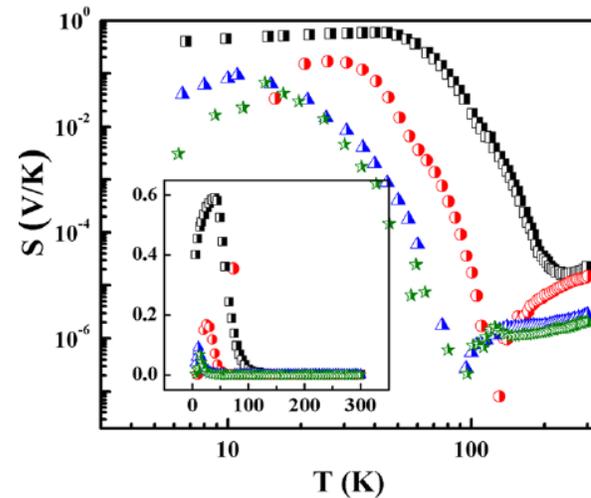
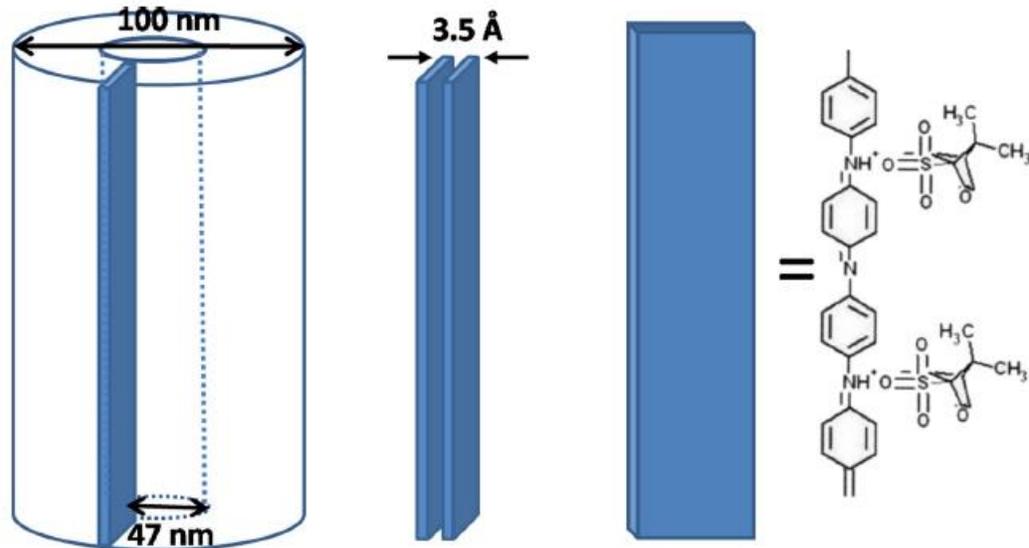
3 Cryogenic magneto-thermoelectrics

- MTE material – tailored to temperature range, S and ZT optimization, and applied magnetic field

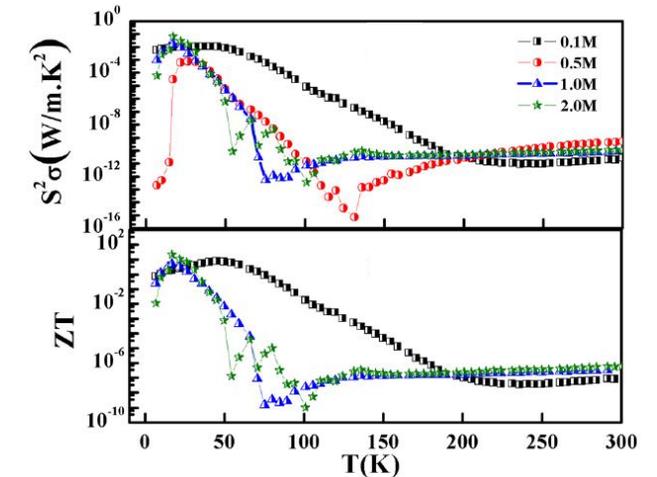


3 Cryogenic magneto-thermoelectrics

- MTE material – novel processing techniques → new (M)TE candidates?



$$S_{max} = 0.6 \mu\text{V/K}$$

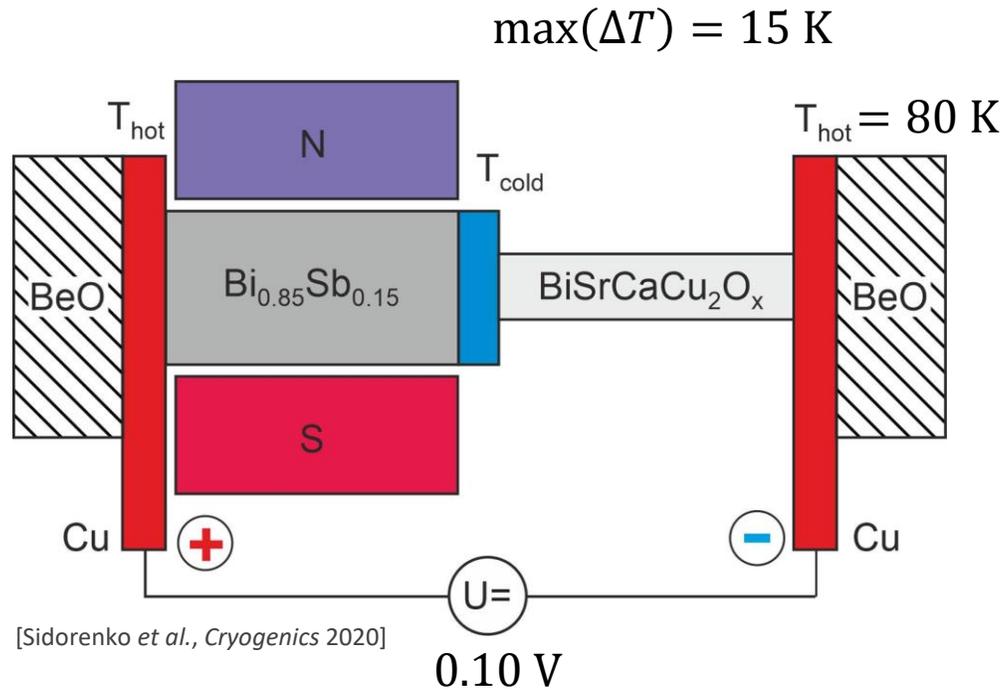


$$(ZT)_{max} = 2.14 [17\text{K}]$$

conducting polymer polyaniline (Pani) doped with camphor sulfonic acid synthesized in semi-crystalline nanostructures

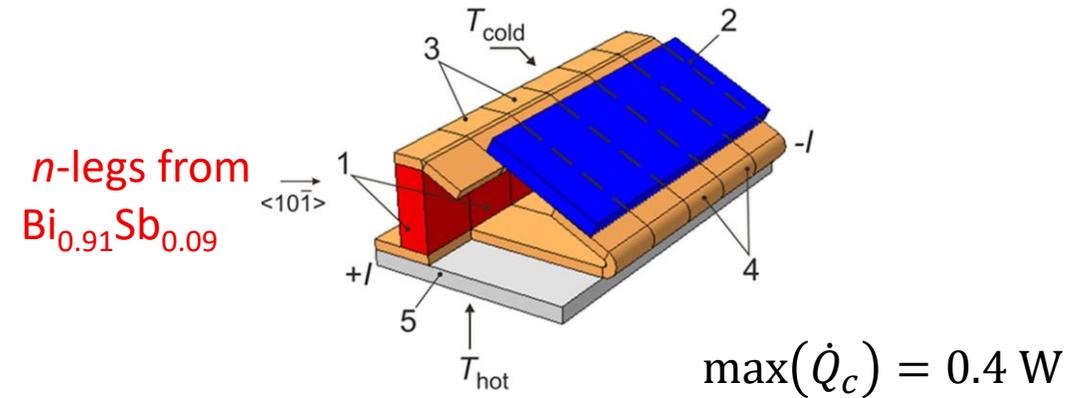
[Nath et al., Applied Physics Lectures 2014]

CRYOGENIC MAGNETO-THERMOELECTRIC COOLER



$$COP = \frac{\dot{Q}_c}{W} = 0.11 - 0.15$$

passive legs based on HTSC ($\text{YBa}_2\text{Cu}_3\text{O}_7$) films



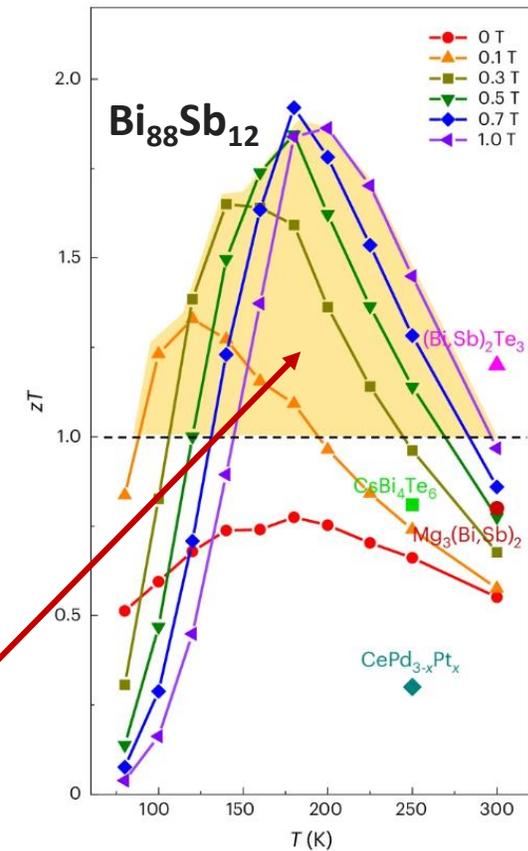
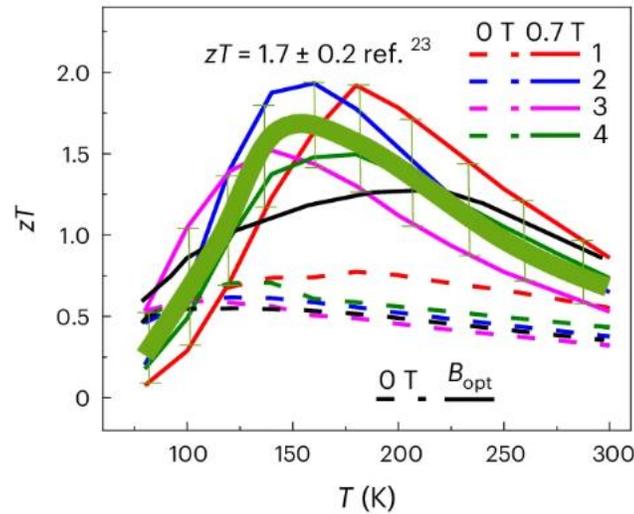
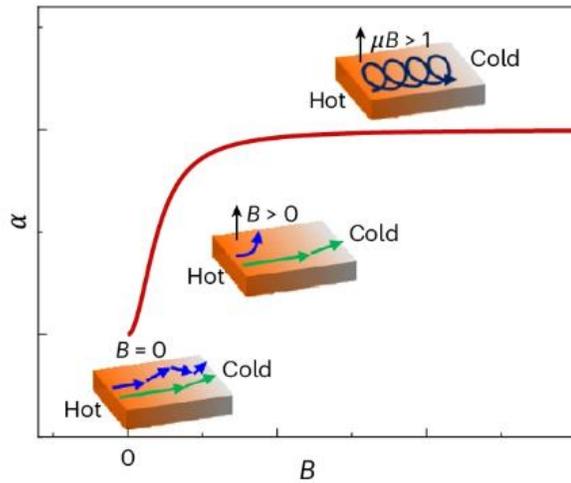
4 Near-room-temperature magneto-thermoelectrics

- **MAGNET type:**
 - **0.3 - 2 T:** permanent magnets ($\text{Nd}_2\text{Fe}_{14}\text{B}$, SmCo)
 - **0.5 - 5 T:** electromagnets – water/air cooling, tunable field strength
 - **5 - 7 T:** PM+ EM hybrid magnets – water/air cooling, tunable field strength
 - **3 - 5 T (at 77 K):** SC magnets – (local) LN_2 cooling, tunable field strength

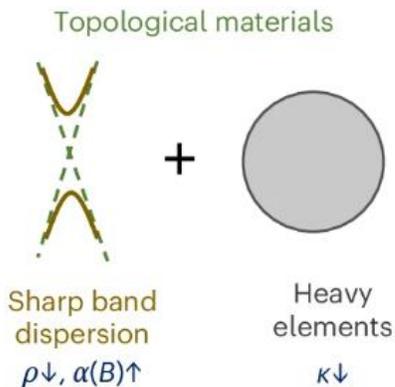
| Material Class | Example Materials | T Range (K) | S (0T) [$\mu\text{V}/\text{K}$] | S (2T) [$\mu\text{V}/\text{K}$] | ZT (0T) | ZT (2T) |
|-----------------------|---|-------------|-----------------------------------|-----------------------------------|------------|-------------|
| Heusler Alloys | Co_2MnSi , Co_2FeAl , Co_2TiSn | 200 – 400 K | 150 – 250 | 180 – 300 | 0.05 – 0.3 | 0.15 – 0.4 |
| Half-Heusler Alloys | CoTiSb , FeNbSb , NiMnSb | 250 – 400 K | 100 – 200 | 130 – 250 | 0.1 – 0.4 | 0.25 – 0.5 |
| Manganites | $\text{La}_{1-x}\text{Ca}_x\text{MnO}_3$, LaSrMnO_3 | 200 – 350 K | 150 – 250 | 180 – 280 | 0.08 – 0.3 | 0.2 – 0.45 |
| Topological Materials | Mn_3Sn , Fe_3Sn_2 , MnBi_2Te_4 | 200 – 350 K | 200 – 300 | 250 – 350 | 0.15 – 0.5 | 0.35 – 0.75 |

4 Near-room-temperature magneto-thermoelectrics

- MTE material:
 - 120 – 350 K: Topological Materials



Potential application:
LOW-TEMPERATURE
THERMOELECTRIC COOLER



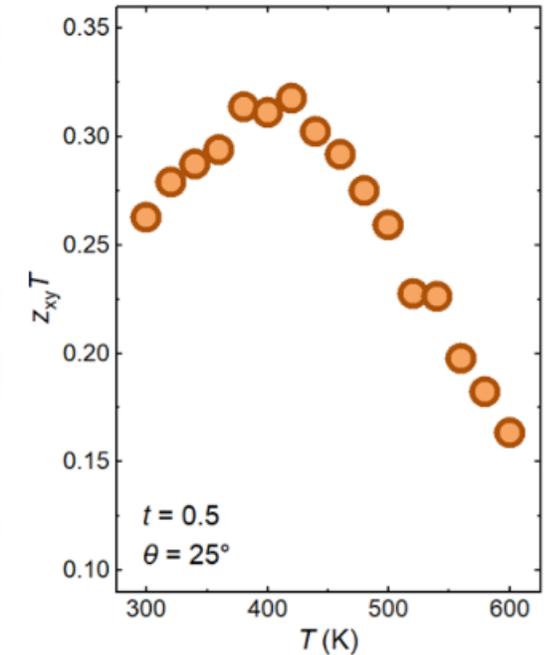
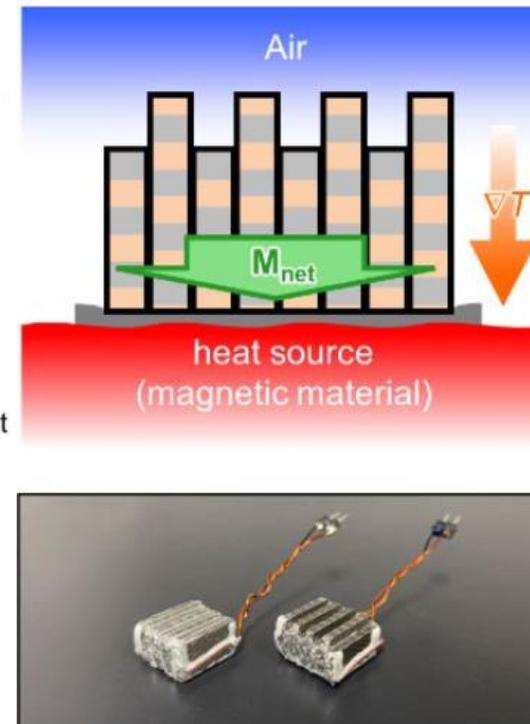
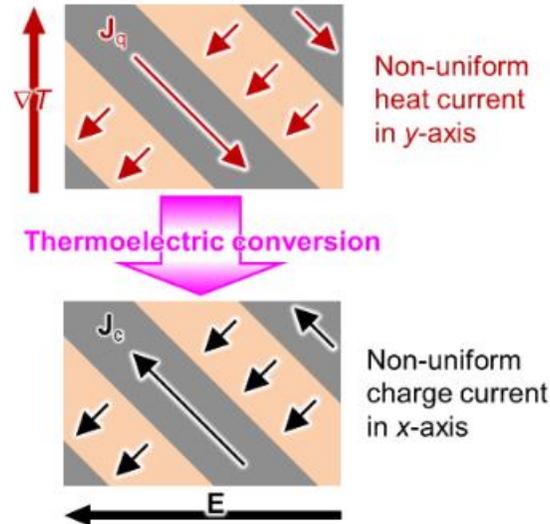
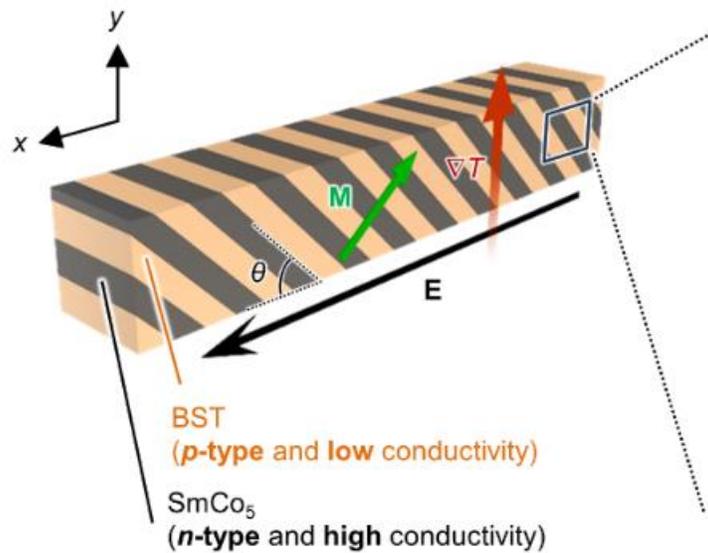
5 High-temperature magneto-thermoelectrics

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| Material Class | Example Materials | T Range (K) | S (0T) [$\mu\text{V}/\text{K}$] | S (2T) [$\mu\text{V}/\text{K}$] | ZT (0T) | ZT (2T) |
|-----------------------------|---|--------------|-----------------------------------|-----------------------------------|-----------|-----------|
| Skutterudites | CoSb_3 , FeSb_3 | 500 – 800 K | 100 – 150 | 120 – 180 | 0.2 – 0.7 | 0.4 – 1.0 |
| Si-Ge Alloys | Si-Ge (p-type, n-type) | 700 – 1000 K | 80 – 120 | 100 – 150 | 0.5 – 1.0 | 0.8 – 1.5 |
| Antiferromagnetic Compounds | $\text{Mn}_{1-x}\text{Cr}_x\text{Sb}$, MnTe | 600 – 900 K | 150 – 250 | 180 – 300 | 0.3 – 0.9 | 0.6 – 1.3 |
| Ferromagnetic Oxides | $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$, SrRuO_3 , Fe_2O_3 | 600 – 1000 K | 100 – 200 | 130 – 250 | 0.2 – 0.8 | 0.5 – 1.1 |

5 High-temperature magneto-thermoelectrics

**Potential application:
HIGH-TEMPERATURE MULTIFUNCTIONAL COMPOSITE MAGNET
ENABLING GIANT TRANSVERSE THERMOELECTRIC CONVERSION**



6 Conclusions

- **magnetic field application enhances thermoelectric performance**
 - enables tunable **Seebeck coefficient (S) and efficiency (ZT)**
 - expands TE applications beyond conventional materials
- **MTE materials – optimized for different temperature regimes and corresponding applications**
 - **Cryogenic:** Bi-Sb, $\text{YBa}_2\text{Cu}_3\text{O}_7$ (HTSC) → quantum & space cooling
 - **Room-T:** Mn_3Sn , Fe_3Sn_2 → magnetic field sensors, cooling
 - **High-T:** Skutterudites, Si-Ge → waste heat recovery
- **MTE applications: magnetic field sensors, energy harvesting, MTE solid-state cooling**
- **challenges & future directions**
 - **thermal management:** control of magnetically induced heating, Joule losses
 - **device optimization:** hybrid magnets and optimal operational temperature ranges, new MTE materials
 - **scalability:** overcoming rare-earth dependency for real-world applications



Thank you.



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