# *Develop Thermoelectric Technology for Automotive Waste Heat Recovery*

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at 2009 DEER Conference, Dearborn, MI
August 5, 2009

Outline
- Introduction
- Engineering Highlights
- Materials Research Highlights
- Future work and Summary

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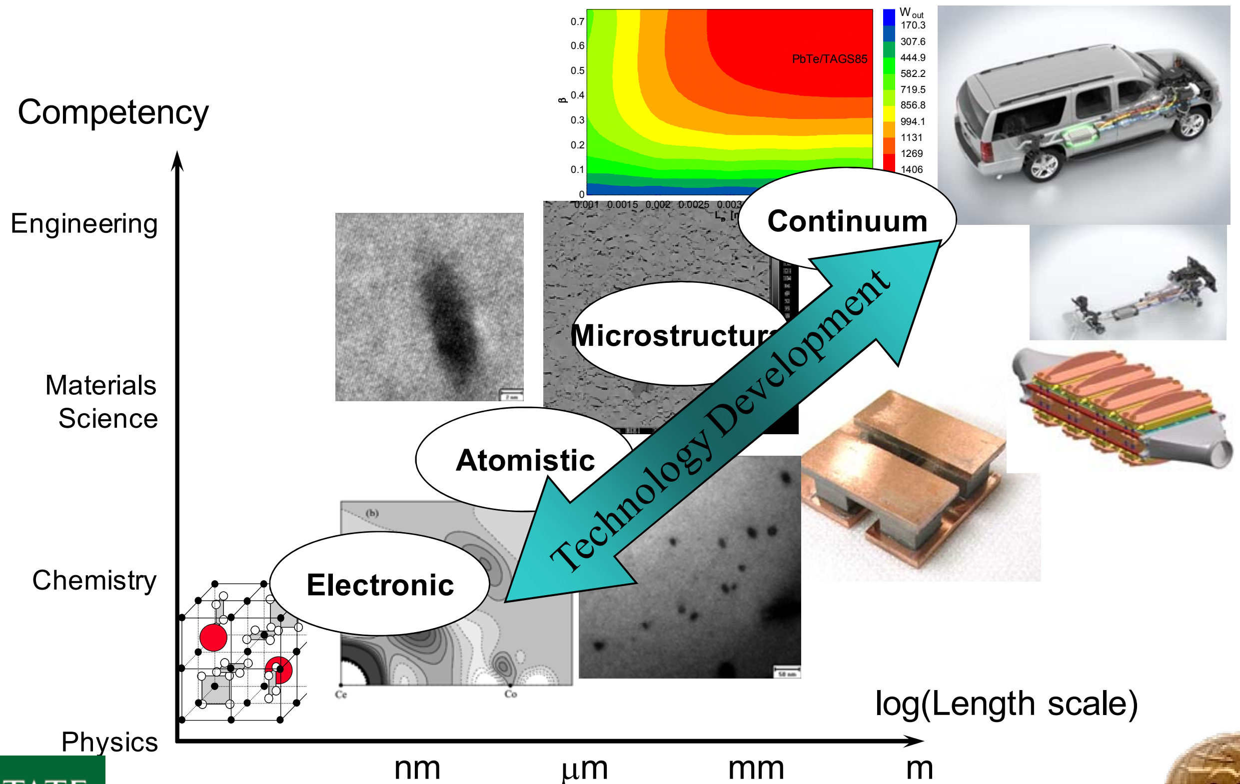
**US Department of Energy**
**Energy Efficiency Renewable Energy (EERE)**
**Waste Heat Recovery and Utilization Research and Development**
**for Passenger Vehicle and Light/Heavy Duty Truck Applications**

# Objectives and Approach

- ❑ Target : 10% fuel economy improvement without increasing emissions
- ❑ Prove Commercial Viability

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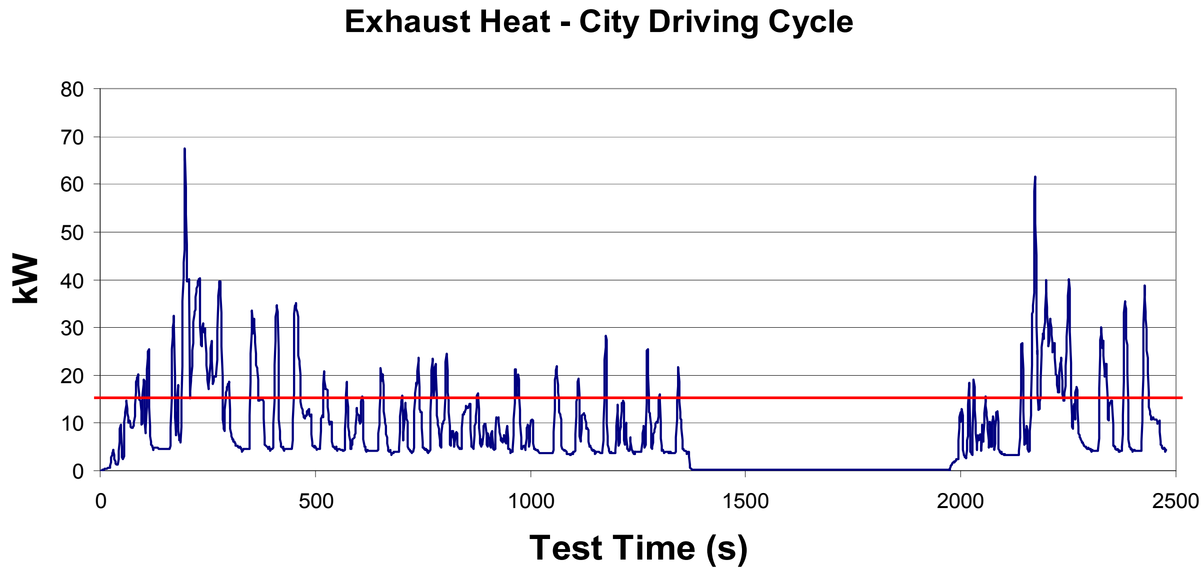
# *Previous Year Accomplishments*

- Finalize TE generator and power electronics design
- Finalize vehicle thermal management and integration
- TE module construction
- Improve material ZT and thermo-mechanical properties

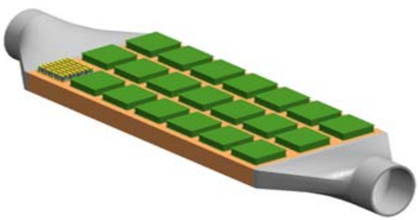
# TE Automotive Waste Heat Recovery Vehicle Selection – Chevy Suburban

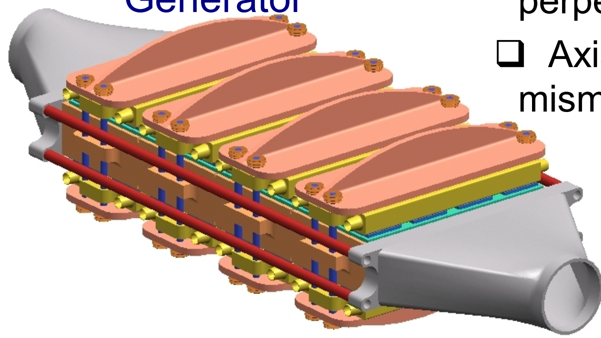



- The Suburban was selected as a test vehicle because it simplified the modifications and installation of the prototype.

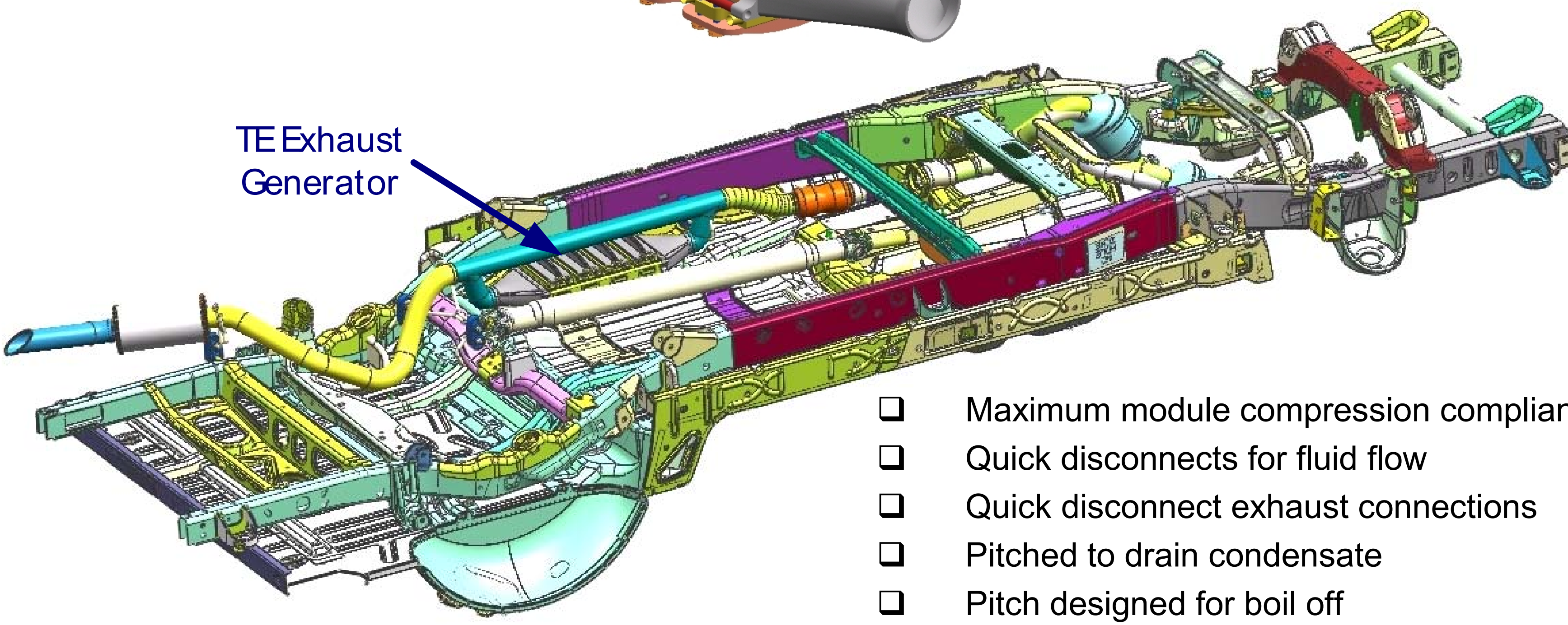
- Fuel efficiency improvement will be better in small, fuel efficient vehicles than in large vehicles because the electrical load in small vehicles is a larger portion of the engine output.

# Exhaust Generator GEN III Design



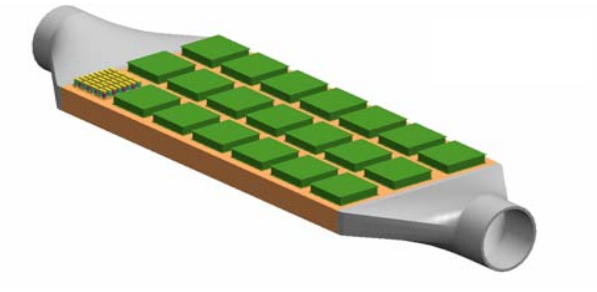



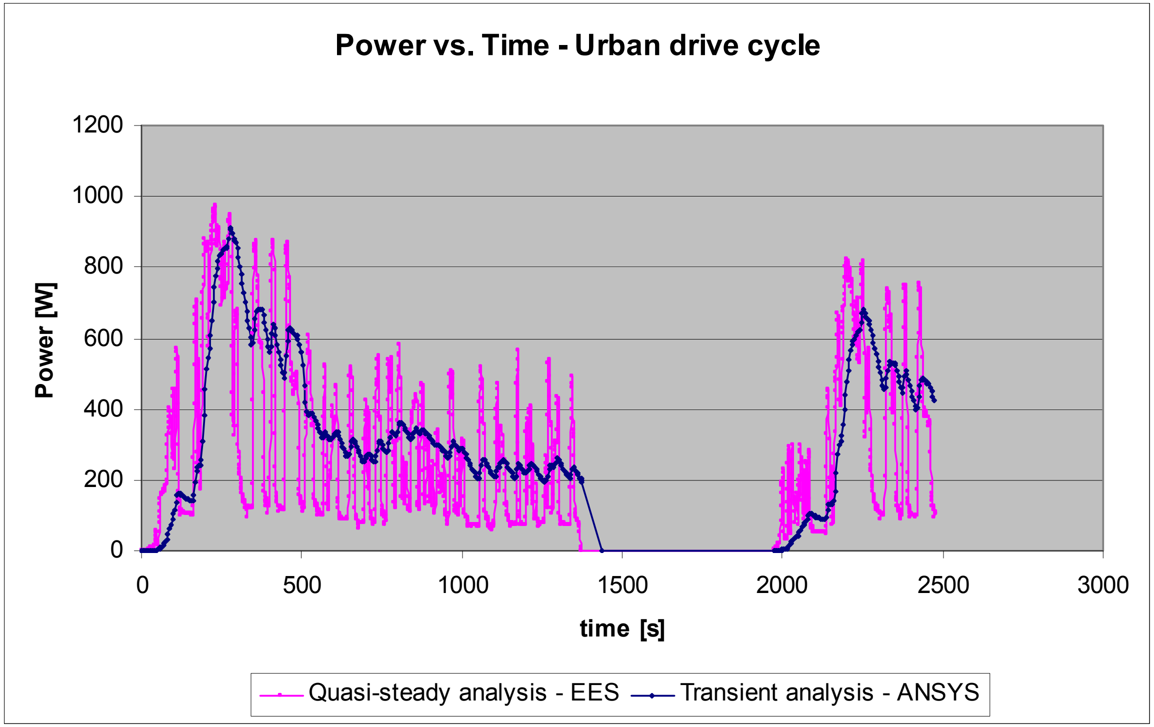

- Located where current muffler is placed; new muffler will be located behind the axle perpendicular to vehicle axis
- Axially compliant for thermal expansion mismatch




- Maximum module compression compliance
- Quick disconnects for fluid flow
- Quick disconnect exhaust connections
- Pitched to drain condensate
- Pitch designed for boil off
- Sealed electronics

# *Subsystem Performance*

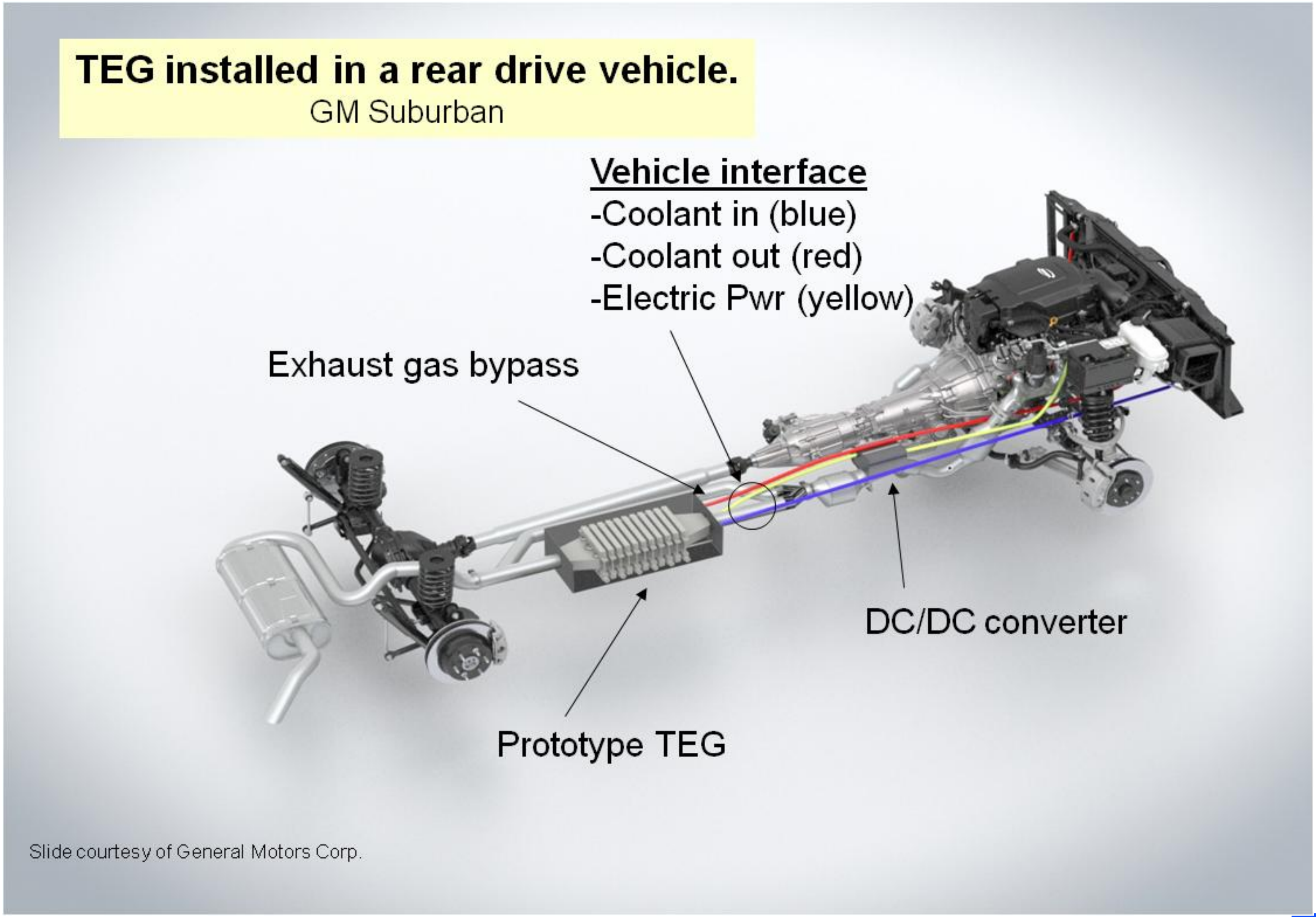





- We expect ~ 1 mpg (~ 5 %) fuel economy improvement for Suburban (average 350 W and 600 W for the FTP city and highway driving cycles, respectively.)

- This technology is well-suited to other vehicle platforms such as passenger cars and hybrids.

# *GM TE Generator on a Chevy Suburban*

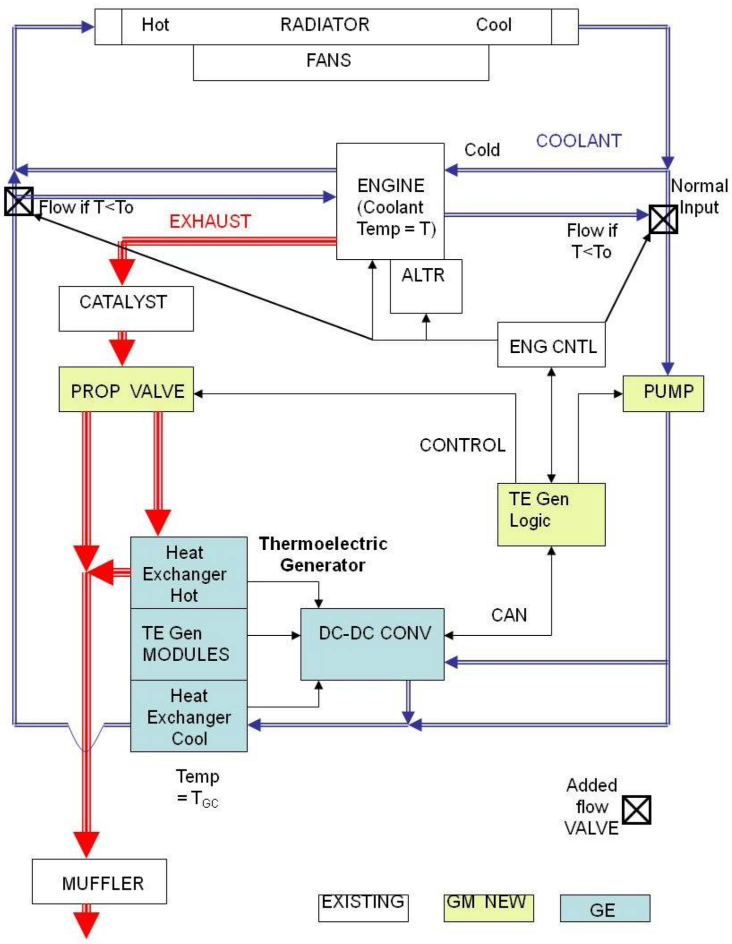


# GM TE Generator on a Chevy Suburban

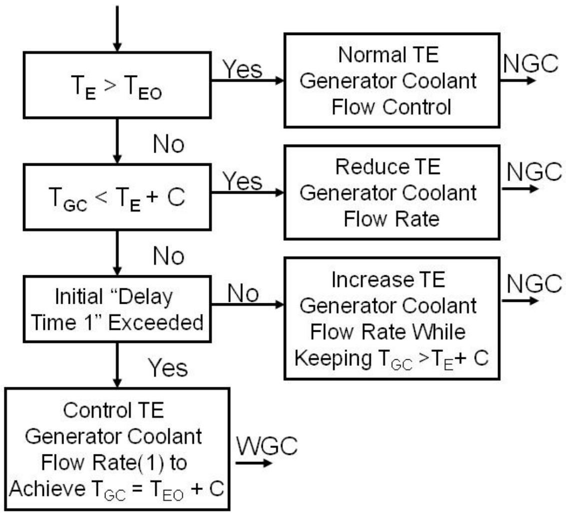
# Generator Animation

# GM TE Generator Thermal Management

## Diagram 1. – Coolant & Exhaust Flow Paths



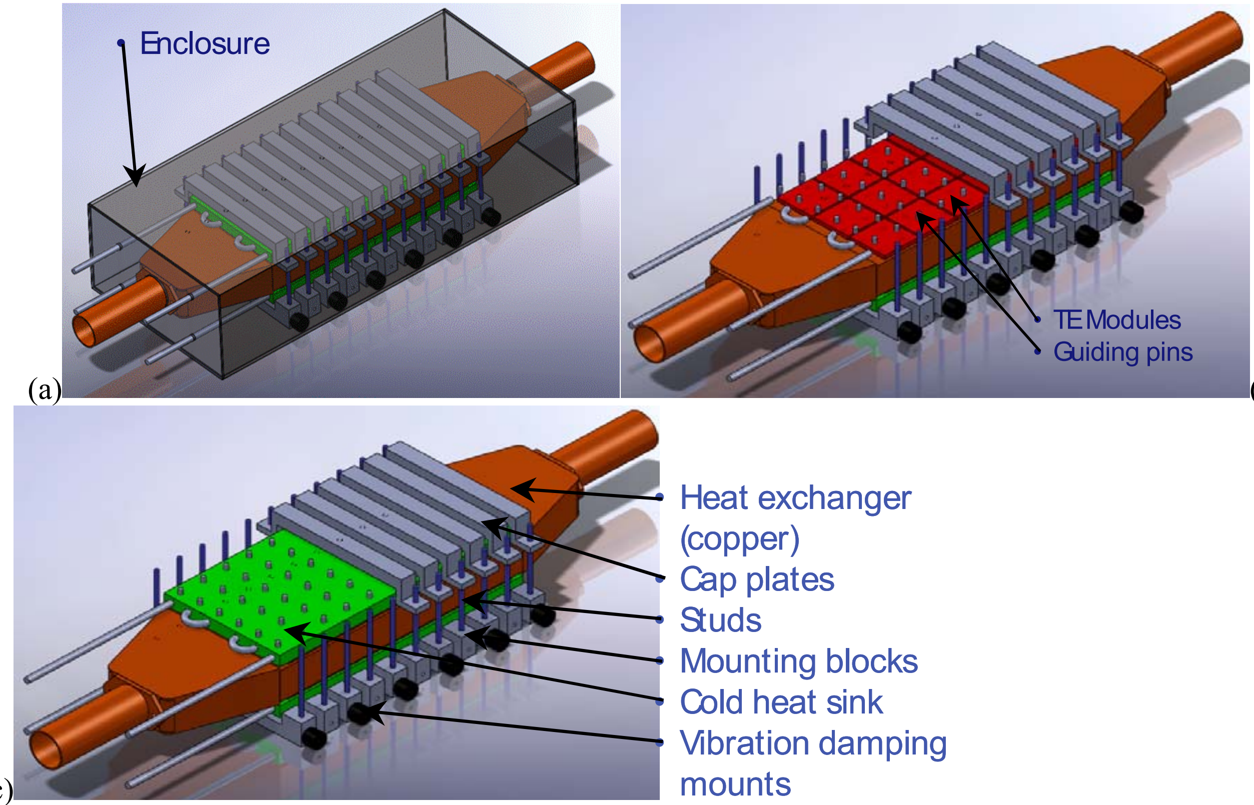

## Diagram 2. - Coolant Flow Logic




- $T_E$ = Engine Coolant Temperature
- $T_{EO}$ = Optimum Engine Coolant Temp
- $T_{GC}$ = TE Generator Cool Side Coolant Temp
- $T_{GH}$ = TE Generator Hot side Temperature
- NGC= Normal TE Generator Coolant Flow path = Input from Radiator Cool Side and Return to Radiator Hot Side
- WGC = Warm-up TE Generator Flow path = Input from Engine Out and return to Engine Input
- C = Temperature Delta between Generator and Engine needed to add heat to engine (typically 5° C)
- Delay Time 1 = Time to move warm coolant from TE Generator to Control Valve (reset when $T_E = T_{EO}$)

(1) Control flow rate to maintain $T_{GC} > T_E + C$ while increasing $T_{GC}$ over N seconds [function of $T_{GH}$, TE Generator Heat transfer, and $T_{EO}$] until $T_{GC} = T_{EO} + C$

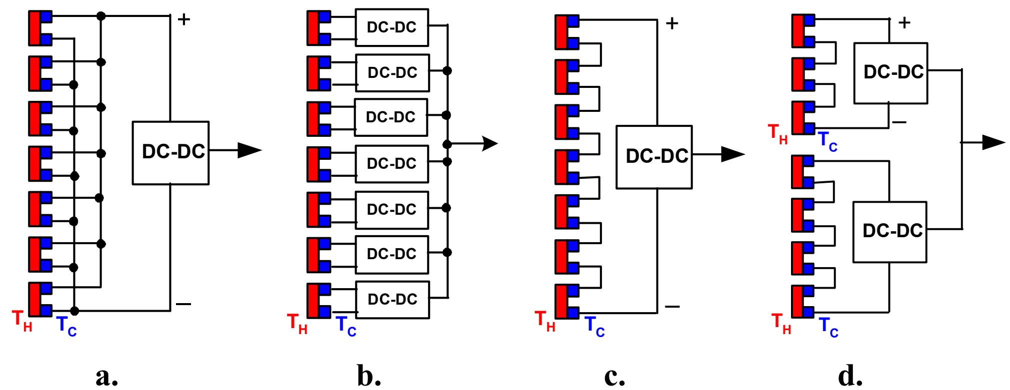
# TE Generator Design



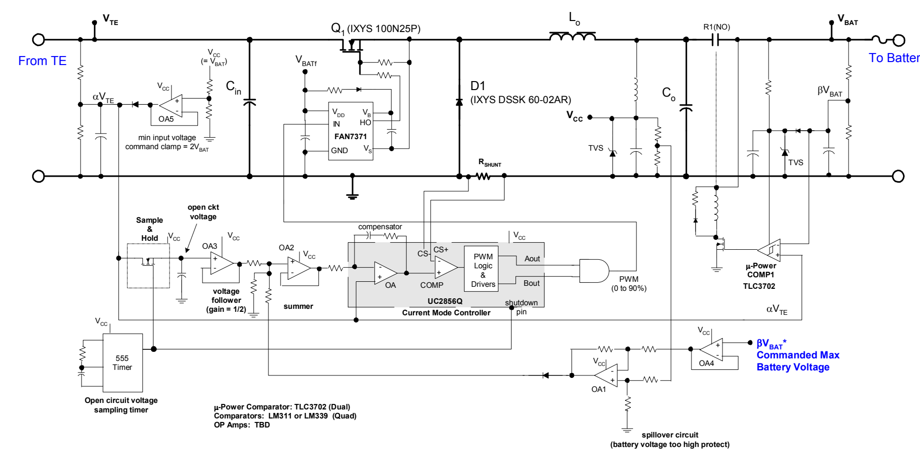

- The generator core is mounted to the enclosure through a series of isolation mounts to isolate harsh shock and vibration
- The enclosure will provide a sealed environment for the generator.
- The enclosure will be stiff in the vertical axis of the generator, so as to provide rigidity

# *Power Electronics*

**Four alternative TE power conversion architectures**

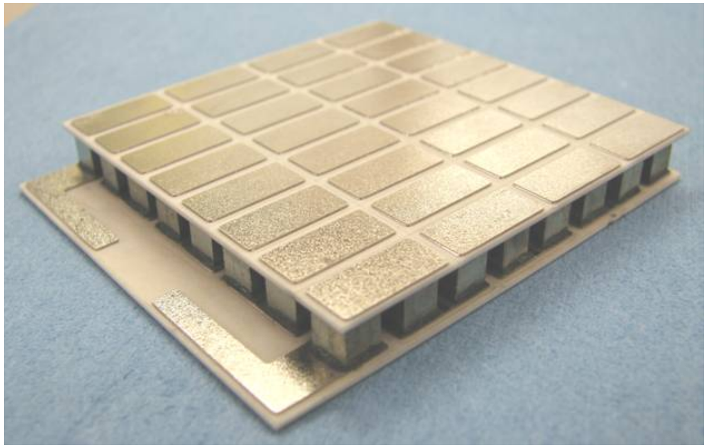


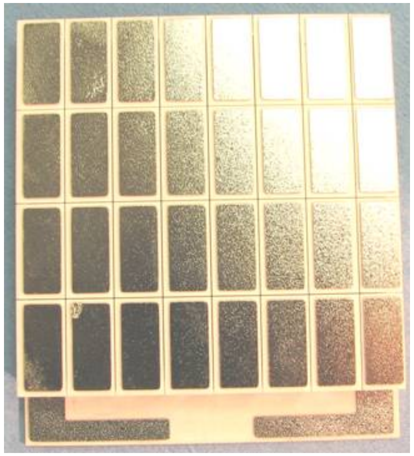

**Functional control block diagram**

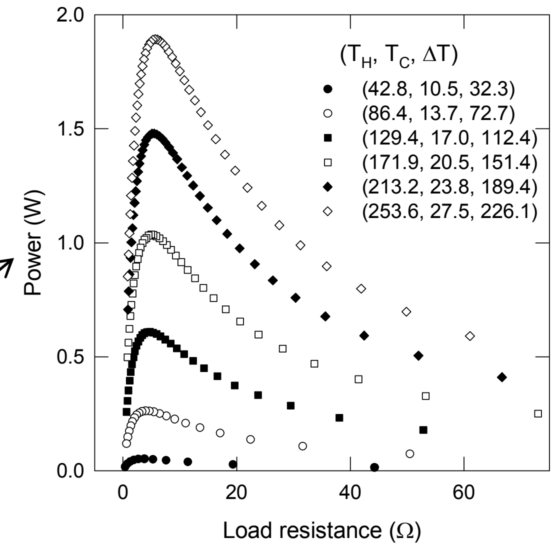


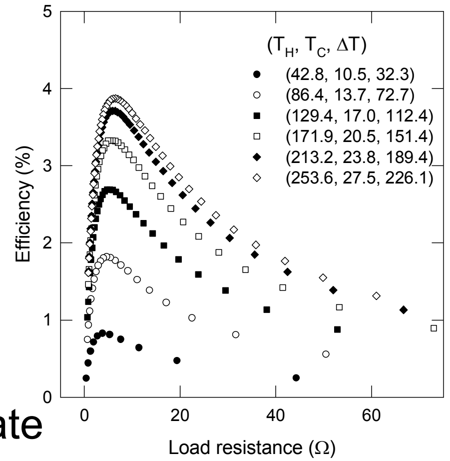

- Completed a trade-off study to determine the electrical topology of the generator and the DC-to-DC converter architecture
- Selected the design that maximizes reliability & efficiency over the driving cycles and minimizes system cost.

# Prototype Modules



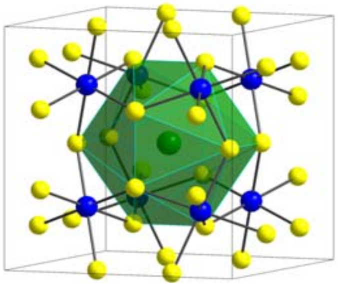


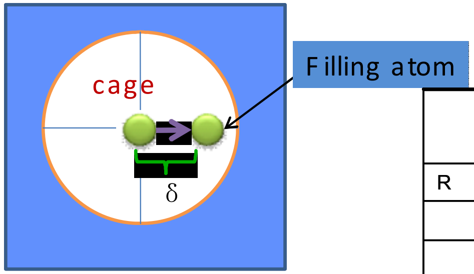



- Developed a novel solid-phase diffusion bonding process to fabricate thermoelectric modules
- Measured performance of some initial modules at various temperature gradients

# Filler Atoms in Skutterudites Rattle with Different Frequencies - Theory






| | | [111] | | [100] | |
|---|---|---|---|---|---|
| R | Mass ($10^{-26}$ Kg) | k (N/m) | $\omega_0$ ($cm^{-1}$) | k (N/m) | $\omega_0$ ($cm^{-1}$) |
| La | 23.07 | 36.10 | 66 | 37.42 | 68 |
| Ce | 23.27 | 23.72 | 54 | 25.18 | 55 |
| Eu | 25.34 | 30.16 | 58 | 31.37 | 59 |
| Yb | 28.74 | 18.04 | 42 | 18.88 | 43 |
| Ba | 22.81 | 69.60 | 93 | 70.85 | 94 |
| Sr | 14.55 | 41.62 | 90 | 42.56 | 91 |
| Na | 3.819 | 16.87 | 112 | 17.18 | 113 |
| K | 6.495 | 46.04 | 141 | 46.70 | 142 |

Small displacement $\delta$ of the filler from it equilibrium *x* will lead to an increase of the total energy of the system.

$$E(x+\delta) = E(x) + \frac{1}{2}\ddot{E}(x)\delta^2 + \frac{1}{6}\dddot{E}(x)\delta^3 + \cdots$$

harmonic term — anharmonic term

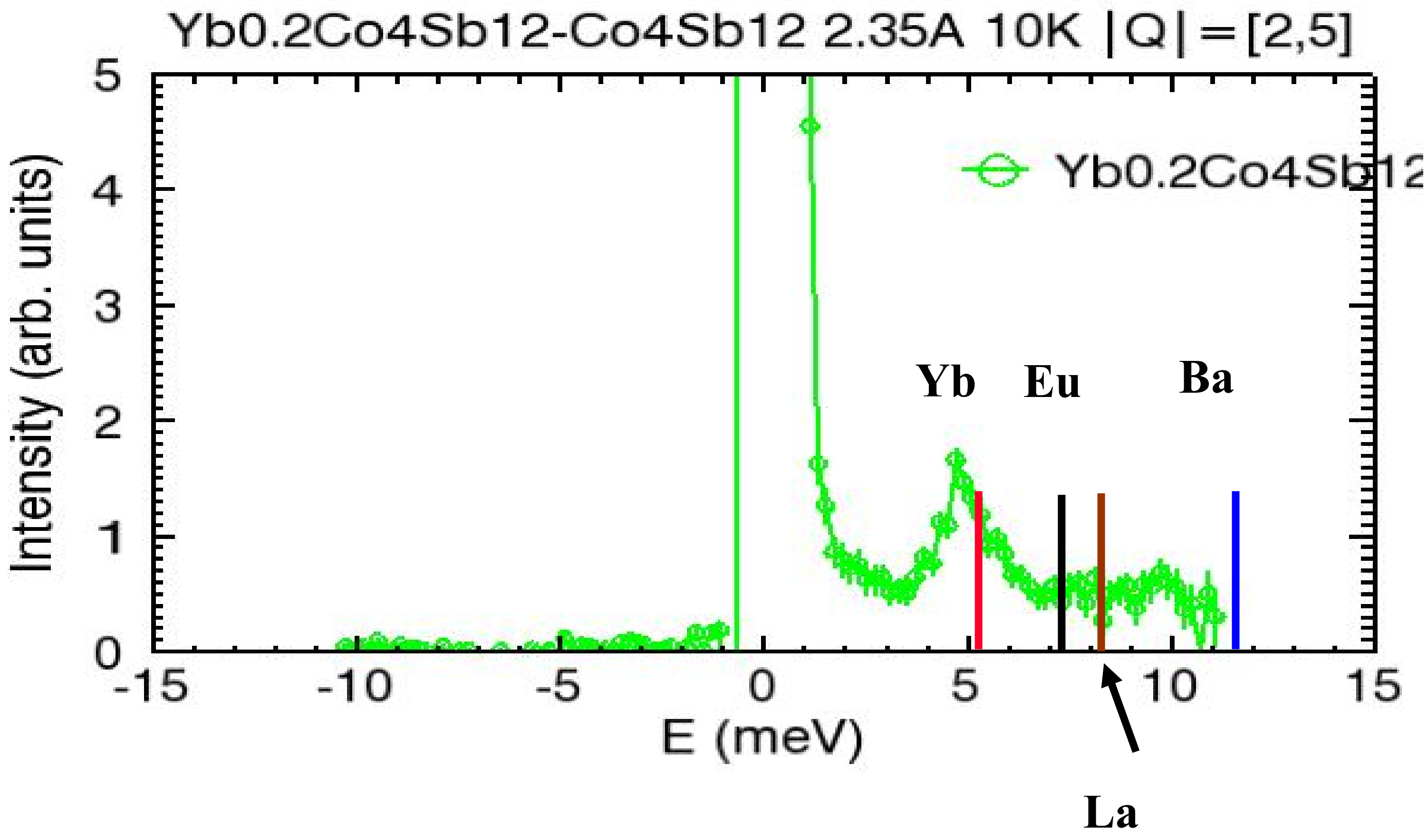
In a harmonic approximation, $\ddot{E}(x)$ is the spring constant.

$$\omega_0 = \sqrt{\frac{\ddot{E}(x)}{m}}$$

- Multiple-element filling will scatter a broad range of lattice phonons, lower thermal conductivity, and improve ZT[1-3]

1. Shi, X., Zhang, X., Chen, L. D., and **Yang, J.**, *Phys. Rev. Lett.* **95**, 185503, 2005.
2. **Yang, J.**, Zhang, W., Bai, S. Q., Mei, Z., and Chen, L. D., *Appl. Phys. Lett.* **90**, 192111, 2007.
3. Shi, X., Kong, H., Li, C.-P., Uher, C, **Yang, J.**, Salvador, J. R., Wang, H., Chen, L., and Zhang, W., *Appl. Phys. Lett.* **92**, 182101, (2008)

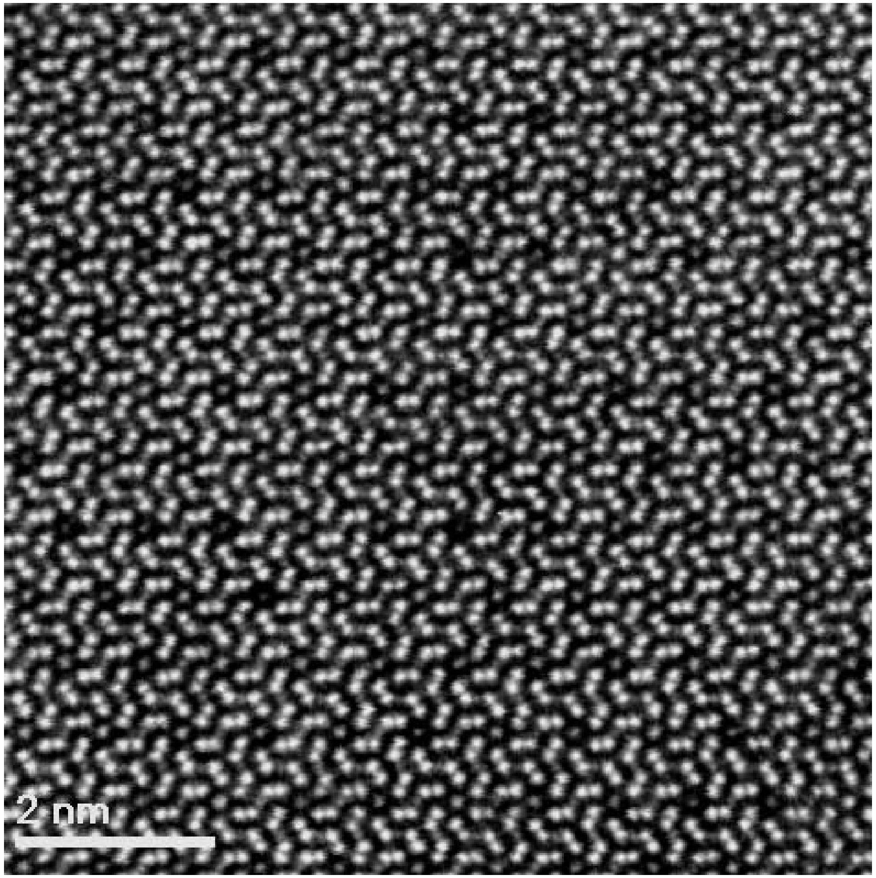
# *Phonon DOS Measured by Inelastic Neutron Scattering – Experiment*

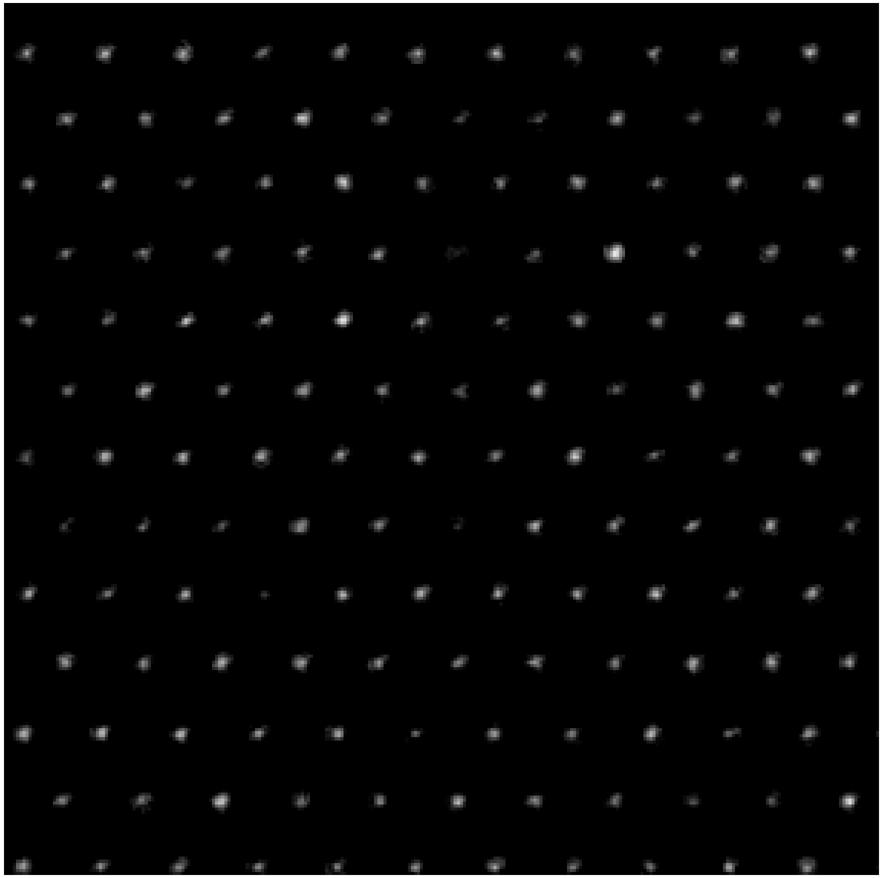



• Calculated resonant phonon frequencies are experimentally validated

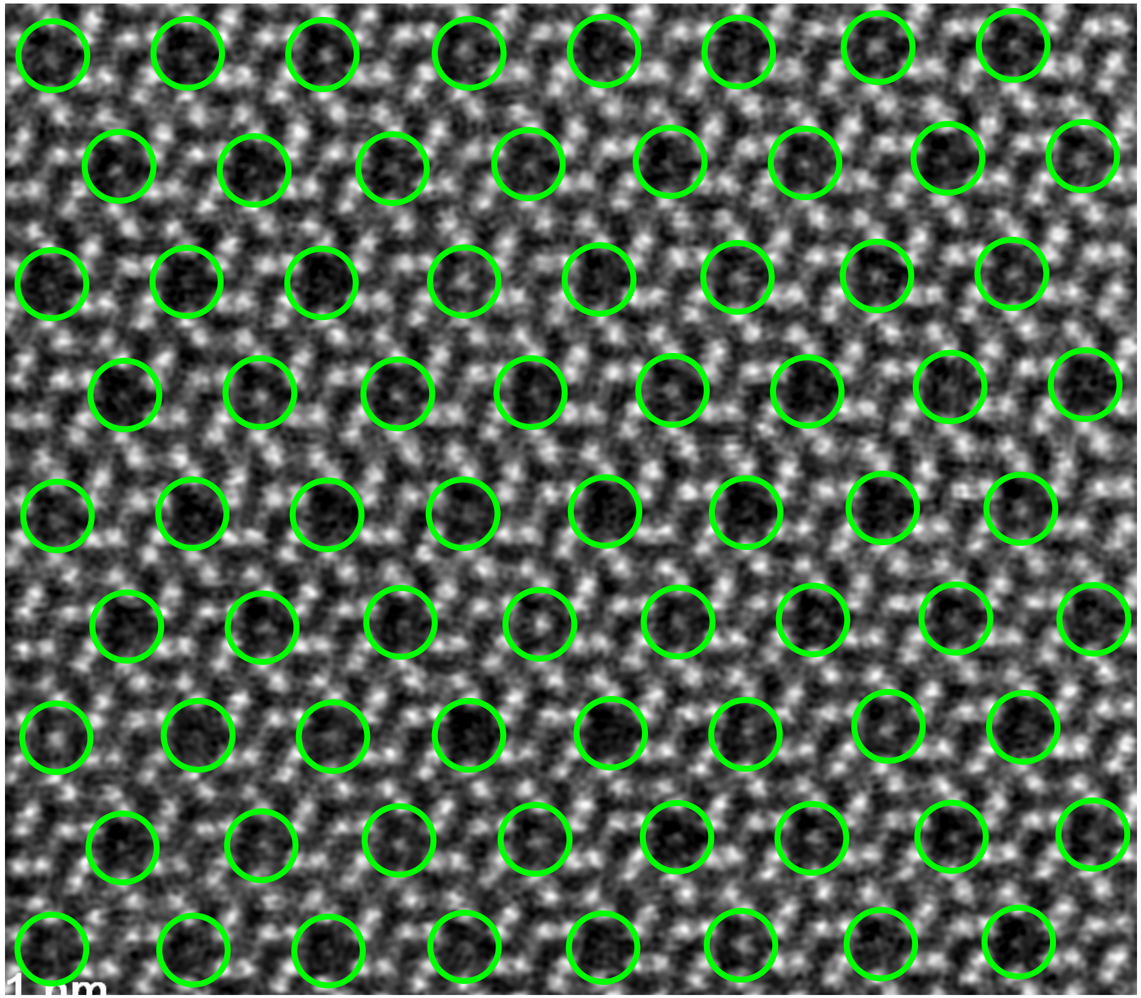
# STEM Images of the Triple-Filled Skutterudites

**[111] direction**

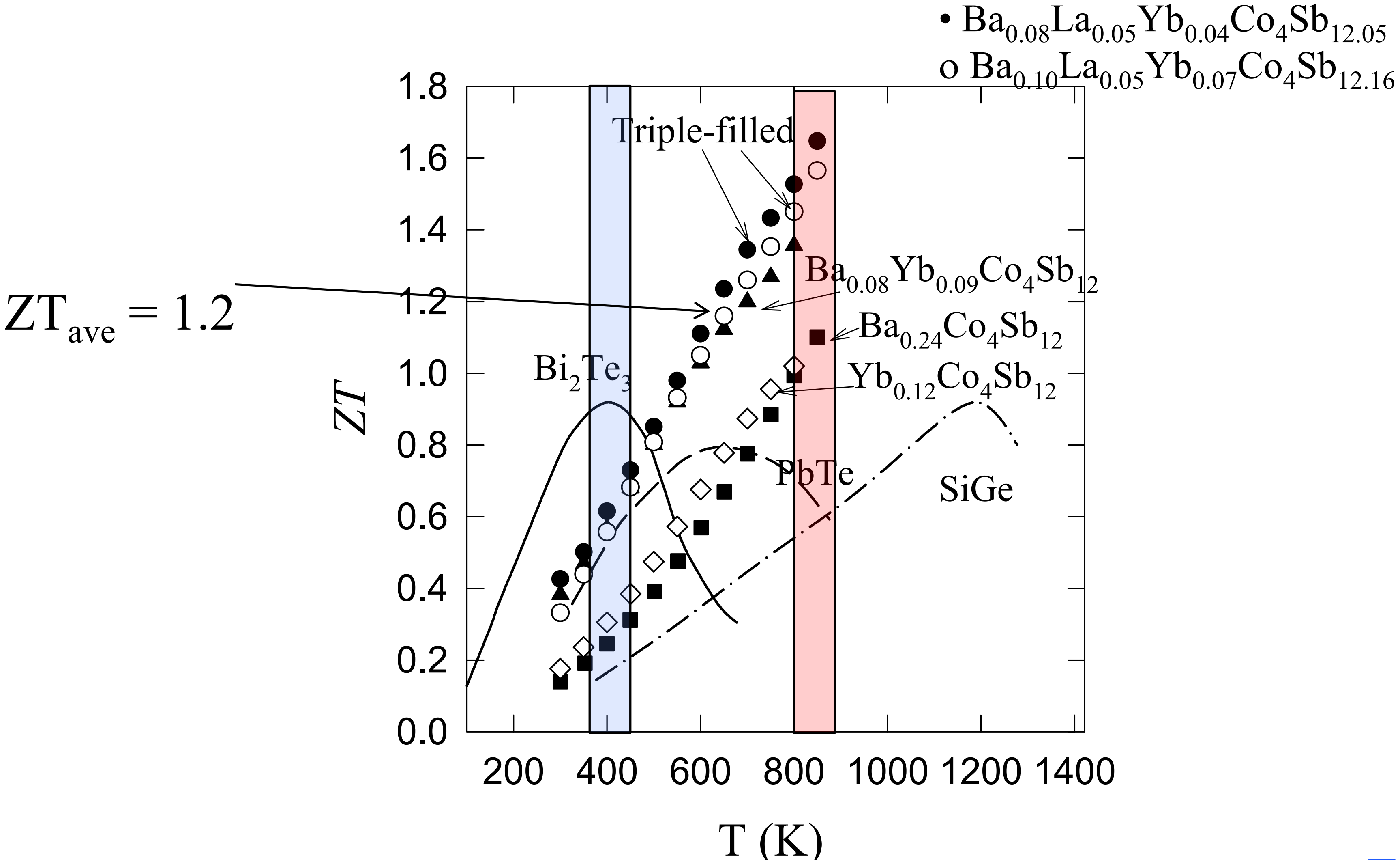


# STEM Images of the Triple-Filled Skutterudites



# Results – Highest ZT Achieved in Triple-filled Skutterudites

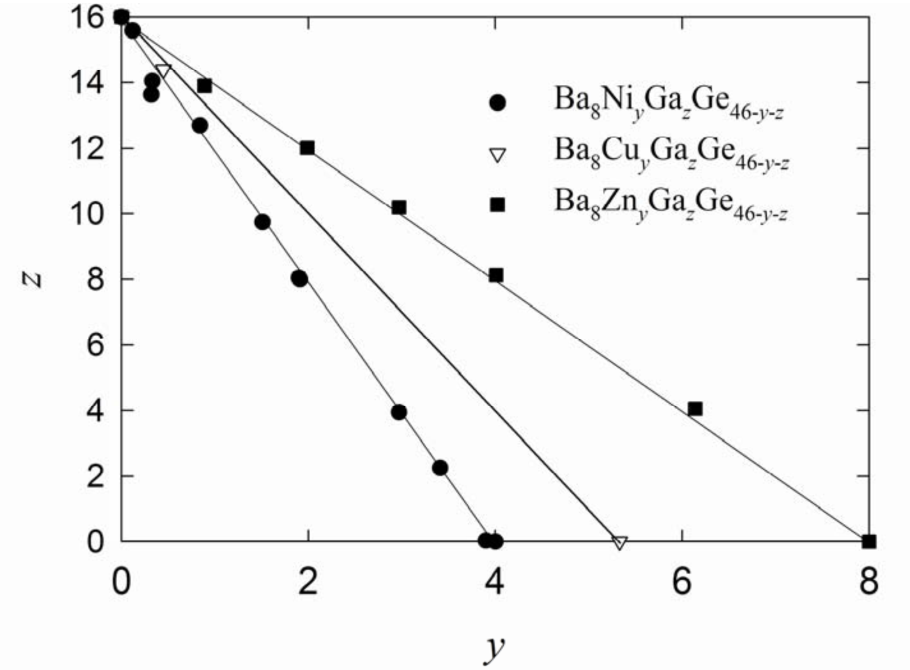



1. X. Shi, et al. Appl. Phys. Lett. **92**, 182101 (2008)
2. X. Shi, et al., submitted (2009)

# Design or Searching for New Clathrates

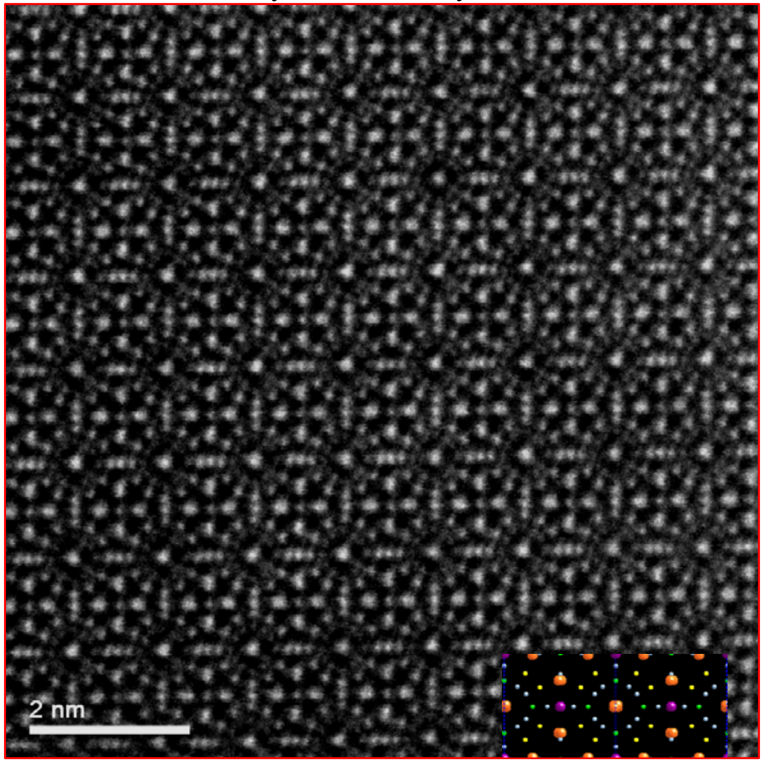
- The basic principle for composition designs: Zintl-Klemm concept.
- Reasonable charge state: -4 for Ni, -3 for Cu, -2 for Zn, and -1 for Ga.

EPMA composition

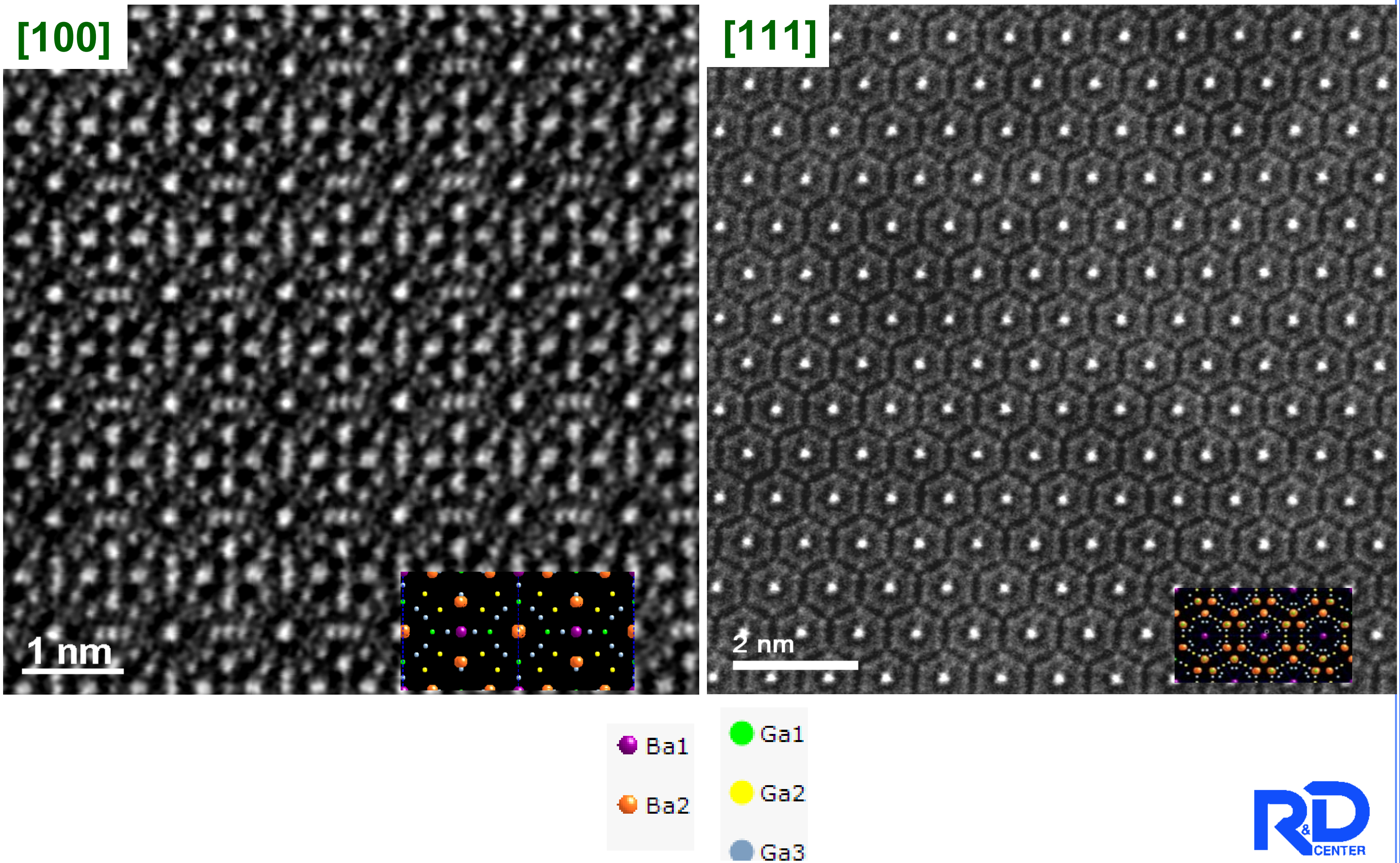


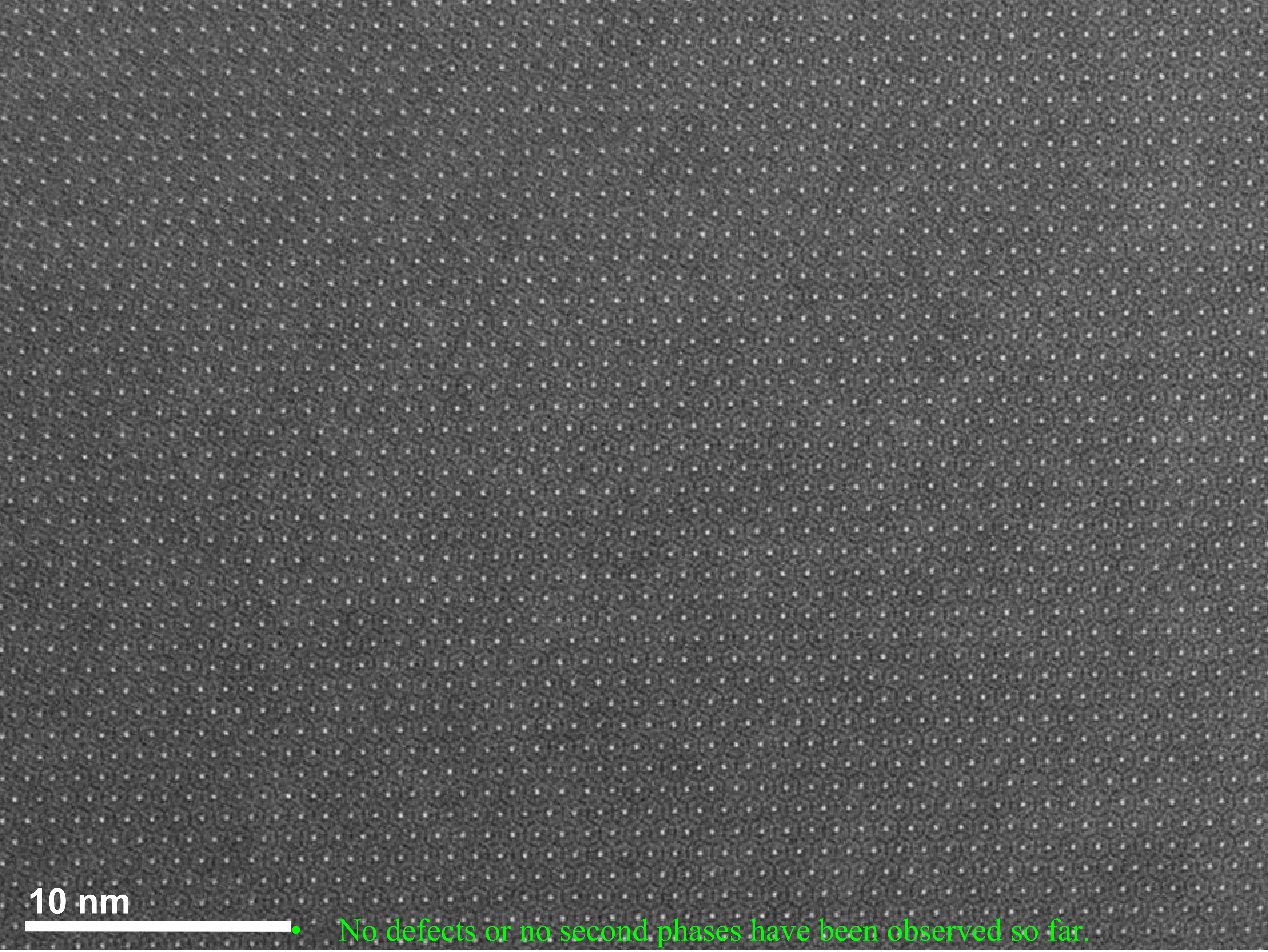

- X-ray and EPMA analysis indicate clathrate structure and composition.
- STEM also confirmed clathrate structure.

$Ba_8Ni_yGa_zGe_{46-y-z}$



# $Ba_8Ni_{0.5}Ga_{14}Ge_{31.5}$

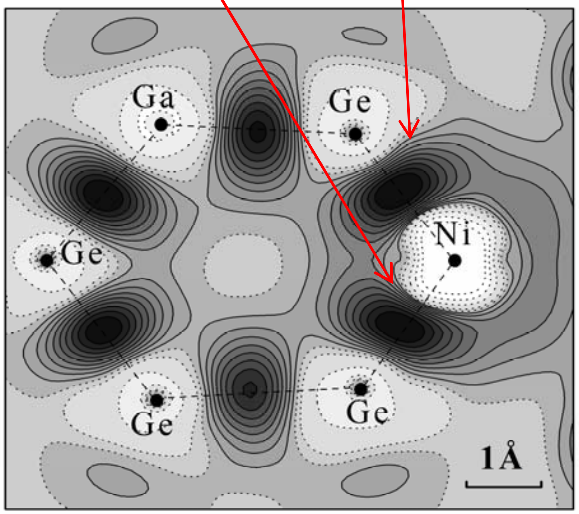



10 nm
No defects or no second phases have been observed so far.

# *Enhanced Thermopower (2)*

Strong charge distortion!

$Ba_8Ni_yGa_zGe_{46-y-z}$



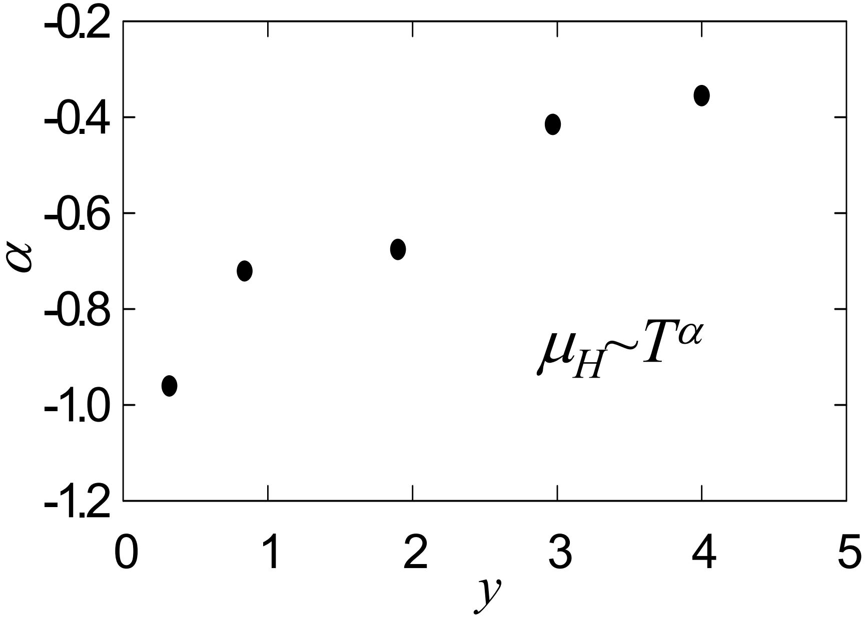

➢Significant ionized impurity scattering of electrons.

$$S \propto (r+3/2)n^{-1/3}$$

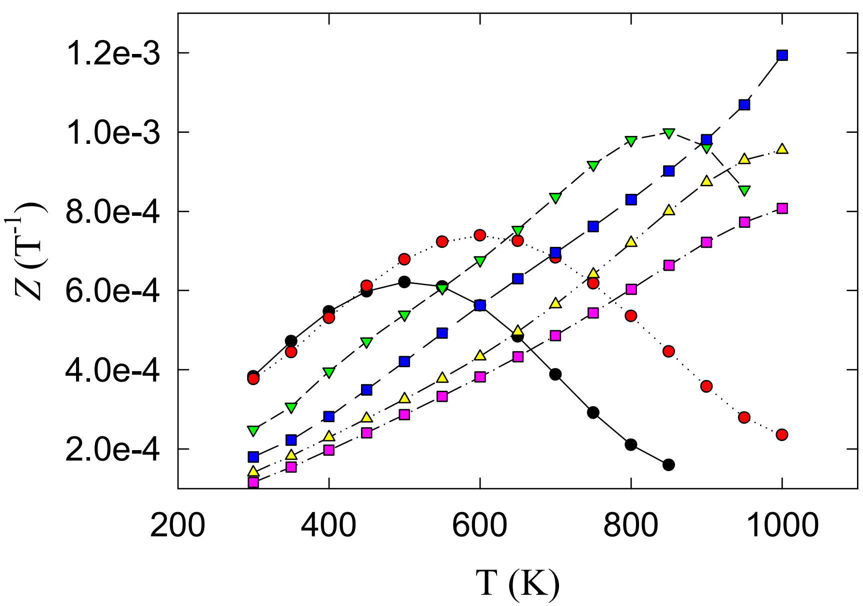
*r=1.5: ionized impurity scattering;*
*r=-0.5: acoustic scattering*

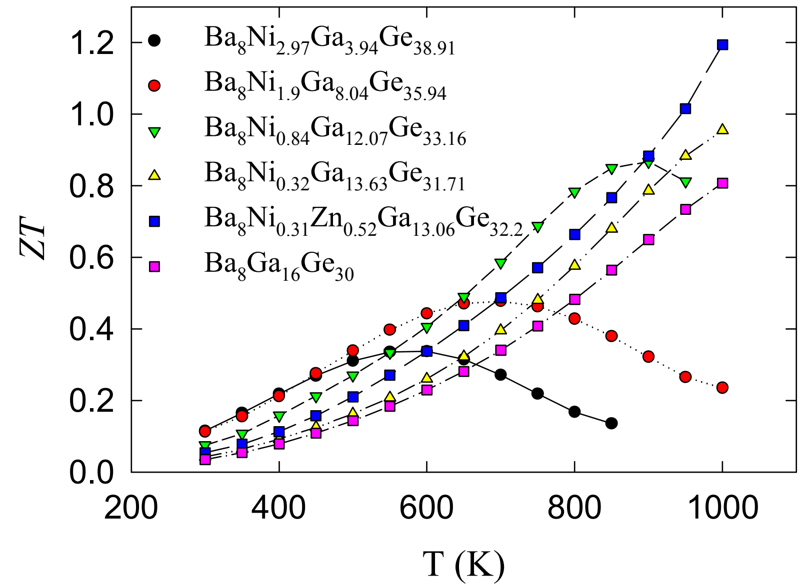
*α=1.5: ionized impurity scattering;*
*α=-1.5: acoustic scattering*

❑Acoustic scattering for $Ba_8Ga_{16}Ge_{30}$
❑Mixed electron scattering



# ZT Designs




- Shifting ZT peaks at any temperature through adjusting the band gap.
- Enhanced thermopower and reduced lattice thermal conductivity.
- ZT Improved more than 200% at low temperatures and 50% at high temperatures.
- $ZT_{max}$=1.2, 50% higher than single $Ba_8Ga_{16}Ge_{30}$.


1. X. Shi, J. Yang, and H. Wang, to be submitted.

# *Future Work*

2009

- Skutterudite-based TE module construction
- Complete the initial subsystem prototype construction

2010

- Provide test data for initial TE subsystem
- Finalize advanced modeling and upgrading based on design
- Finalize vehicle integration with TE waste heat recovery system and the necessary vehicle modification
- Carry out dynamometer tests and proving ground tests for vehicle equipped with TE waste heat recovery subsystem
- Demonstrate fuel economy gain using TE waste heat recovery technology

# *Summary*

- Completed TE Generator design
- Completed power electronics design
- Skutterudite-based module in process
- Prototype construction and installation in process
- Record $ZT_{max}$=1.7 and $ZT_{ave}$=1.2 achieved

| | Average Output [W] | Maximum Output [W] |
|---|---|---|
| FTP-75 | 349 | 957 |
| HWFET | 595 | 813 |
| US06 | 808 | 1233 |
| US06 w/bypass | 628 | 809 |