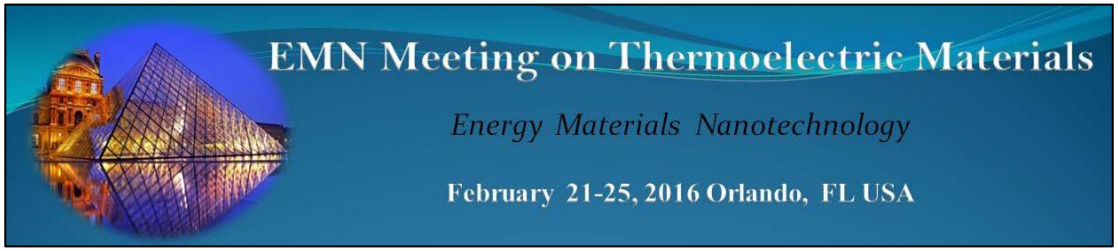
Thermoelectric Generators (TEG) with high power density for application in hybrid cars



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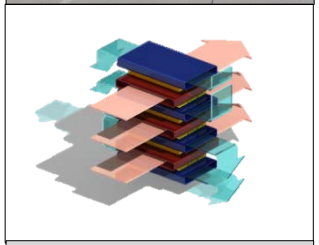
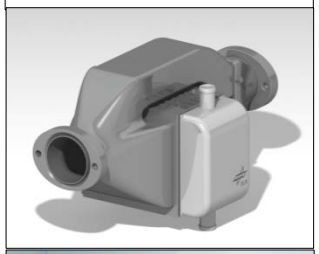


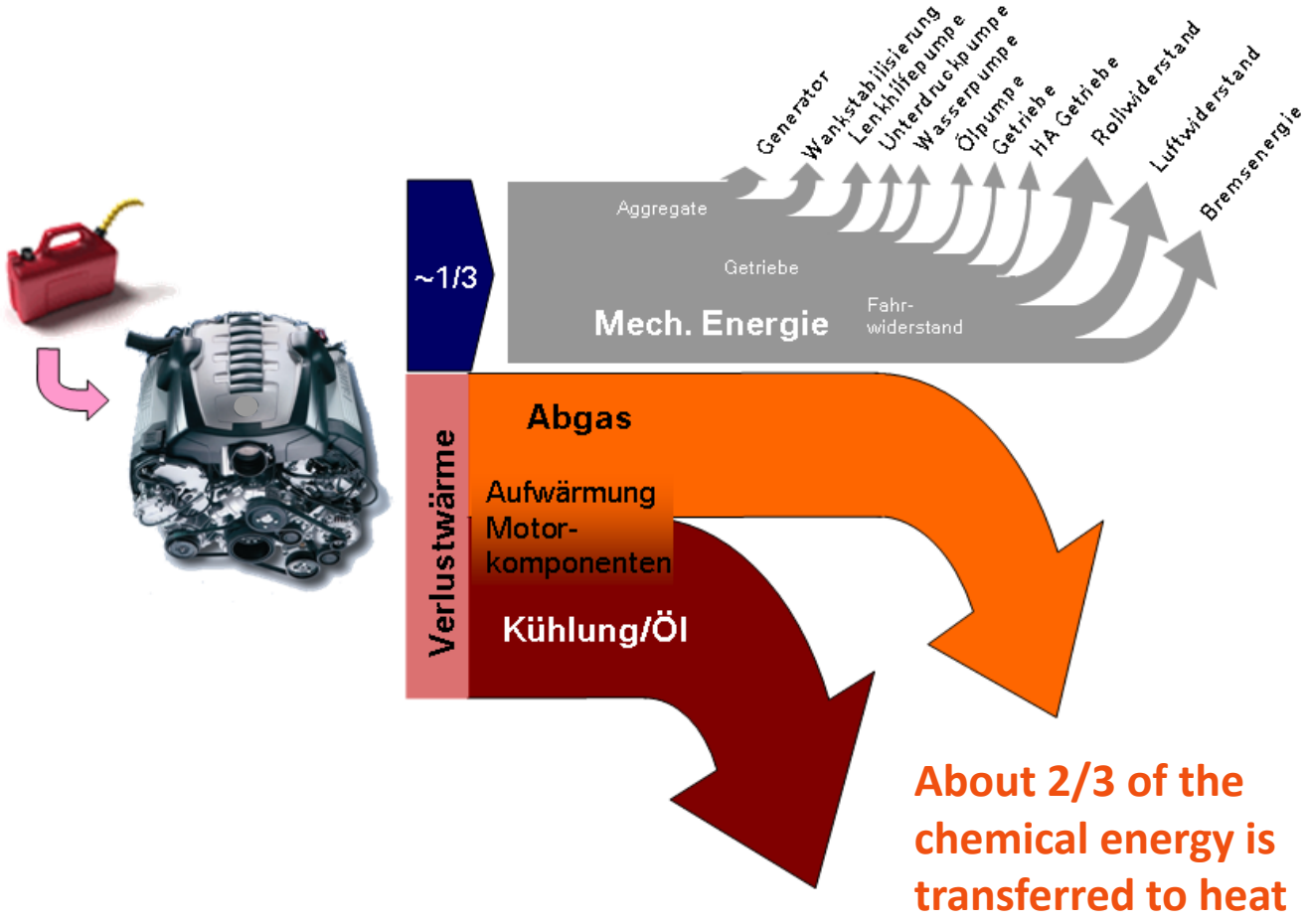


Outline

- Motivation Waste Heat Recovery
- Vehicle Measurements and Boundary Conditions
- Procedural method for increasing of power density
  - Power Increase
  - Weight and Volume Reduction
- Simulation and Measurement Results

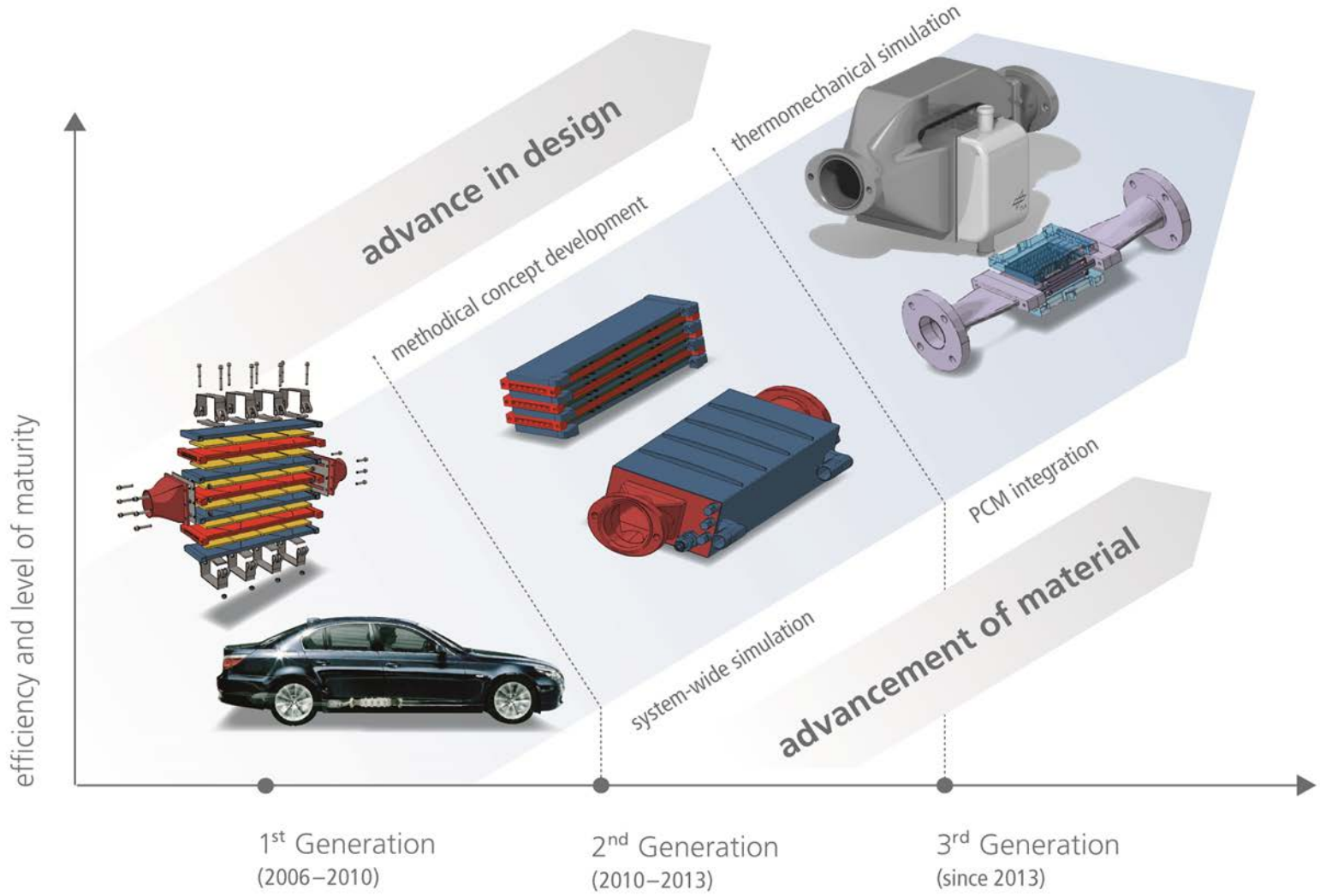
Motivation Waste Heat Recovery

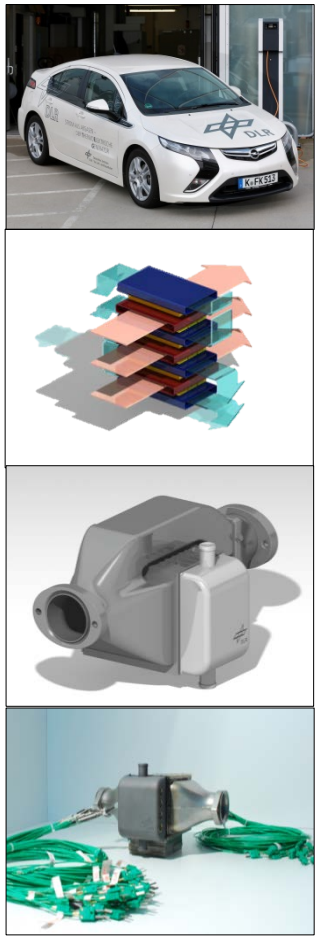
Energy flow of Combustion Engines



1) Treffinger P., Häfele Ch., Weiler T. DLR e.V. Stuttgart; Eder A., Richter R., Mazar B. BMW Group München: Energierückgewinnung durch Wandlung von Abwärme in Nutzenergie. 2008 VDI Tagung „Innovative Fahrzeugantriebe“, Dresden

The Evolution of the TEG at the DLR





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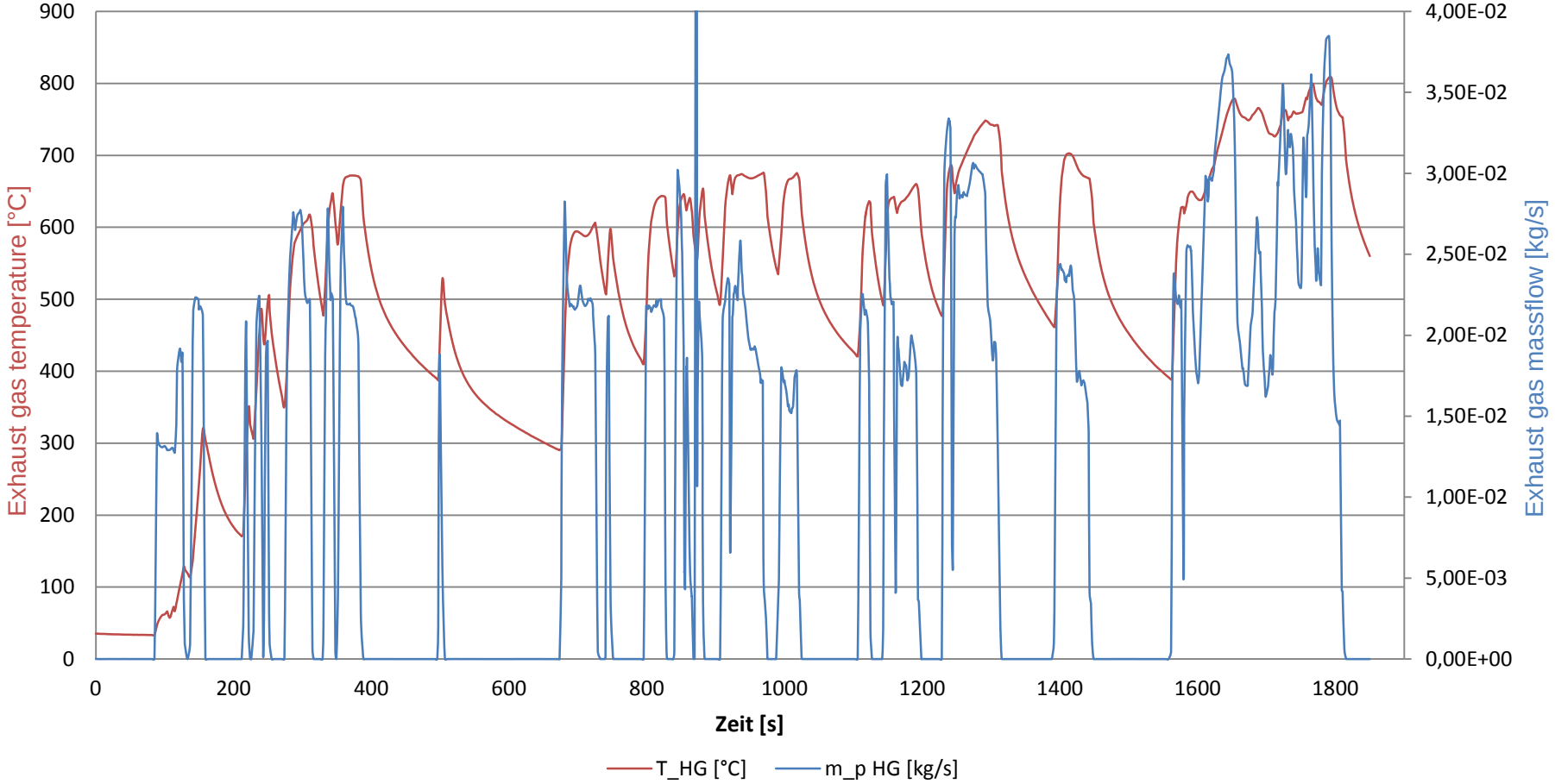
WLTC – driving cycle

Opel Ampera 1.4 l Hybrid (63 kW)

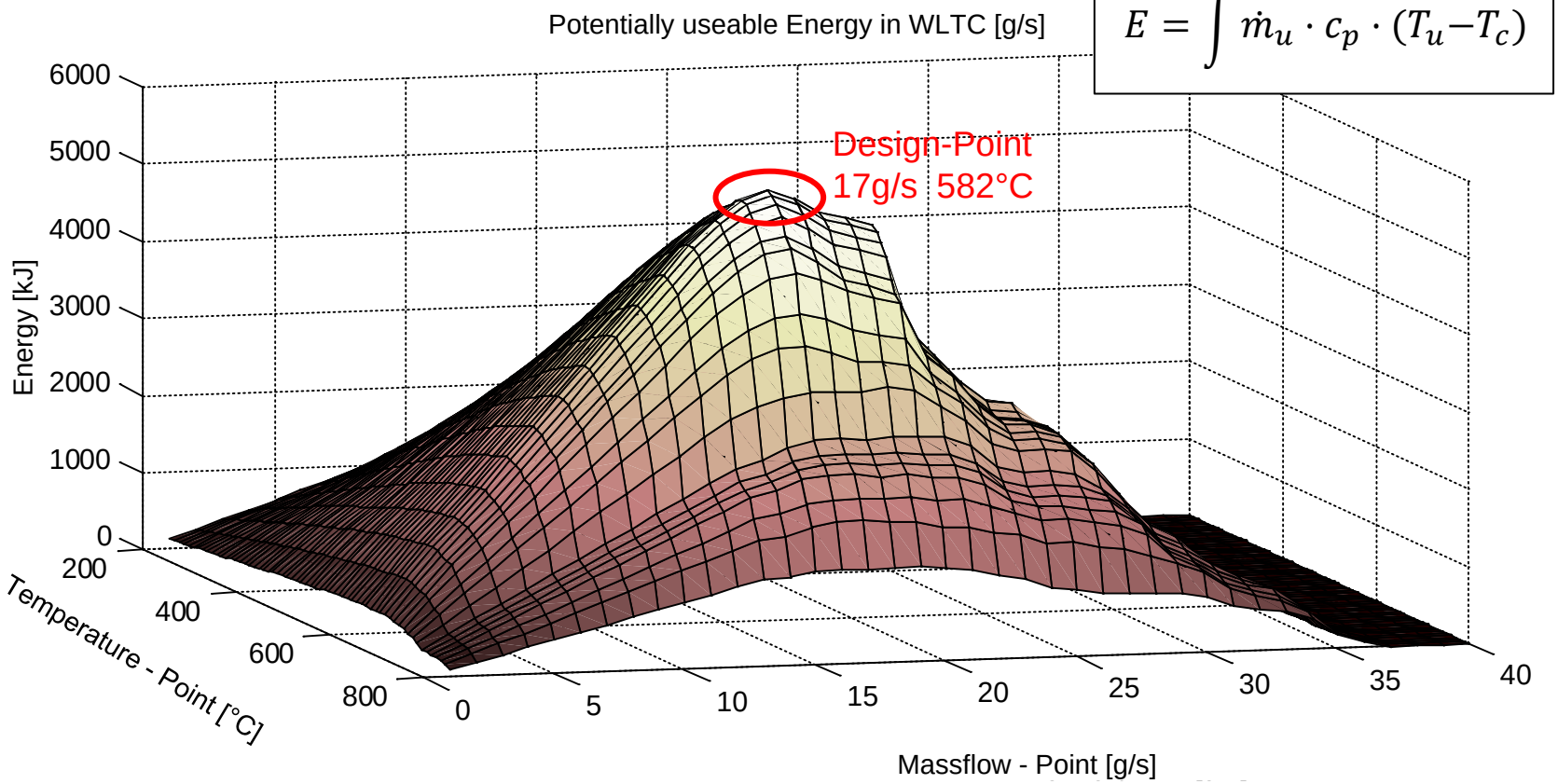


1) Oetringer, Kerstin und Kober, Martin (2014) *Hat der TEG noch eine Berechtigung in einer Zeit der Elektromobilität?* VDI-Fachkonferenz Thermische Rekuperation in Fahrzeugen, 31. März - 01. April 2014, Nürtingen, Deutschland..

Choosing a TEG-Design-Point

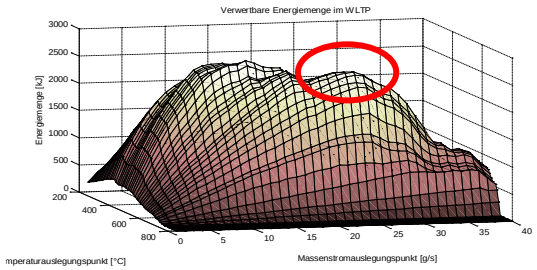
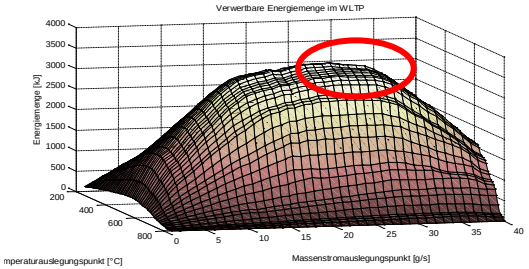
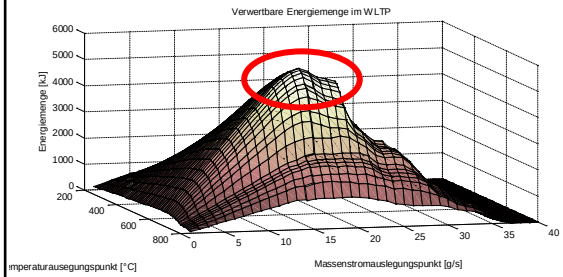
Which Design-Point contains most energy?

$$E = \int \dot{m}_u \cdot c_p \cdot (T_u - T_c)$$



1) Oetringer, Kerstin und Kober, Martin (2014) *Hat der TEG noch eine Berechtigung in einer Zeit der Elektromobilität?* VDI-Fachkonferenz Thermische Rekuperation in Fahrzeugen, 31. März - 01. April 2014, Nürtingen, Deutschland..

Comparison of Different Vehicle Concepts

Conventional Vehicle	Mild Hybrid	Full Hybrid / Rex
		
		
max. 2500 kJ	max. 3000 kJ	max. 5000 kJ

1) Oetringer, Kerstin und Kober, Martin (2014) *Hat der TEG noch eine Berechtigung in einer Zeit der Elektromobilität?* VDI-Fachkonferenz Thermische Rekuperation in Fahrzeugen, 31. März - 01. April 2014, Nürtingen, Deutschland..

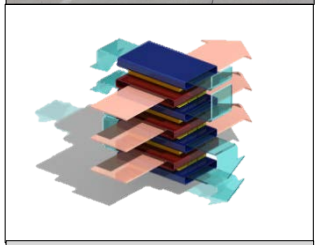
There is already a heat recovery system in a hybrid car

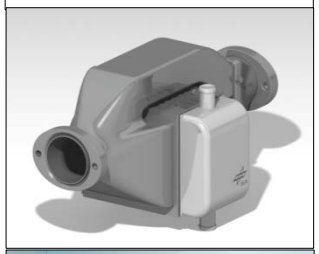
- Toyota Prius III – Exhaust Heat Recirculation (EHR)
  - Coolant passed through the exhaust silencer: standard equipment in the Toyota Prius III - Plug-in Hybrid
  - Shortening of warm-up
  - More efficient heating of the passengers compartment

1)

Demonstration model: Prius III –
Exhaust Heat Recirculation (without thermoelectricity)
Reference: www.priuswiki.de - Exhaust Heat Recovery

1) www.priuswiki.de - Exhaust Heat Recovery





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  - Power Increase
  - Weight and Volume Reduction
- Simulation and Measurement Results

Procedural method for increasing of power density

Goal 1: Power Increase + Cost Reduction

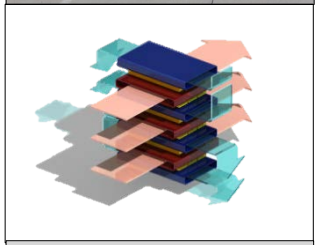
Solution:

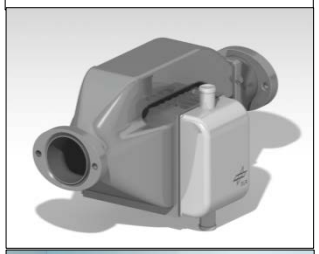
- Holistic Thermodynamic Design-Method for TEG

Goal 2: Weight / Volume Reduction + Cost Reduction

Solution:

- Highly Integrated TEG-Design





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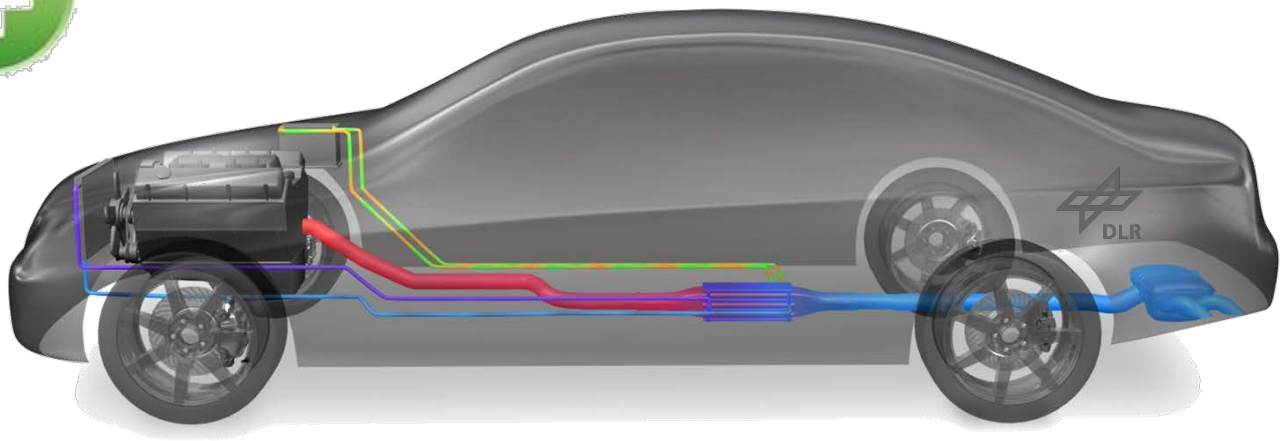
System Development

Shortening the cold start phase

Electrical TEG power

Cooling load / pump power



Back pressure

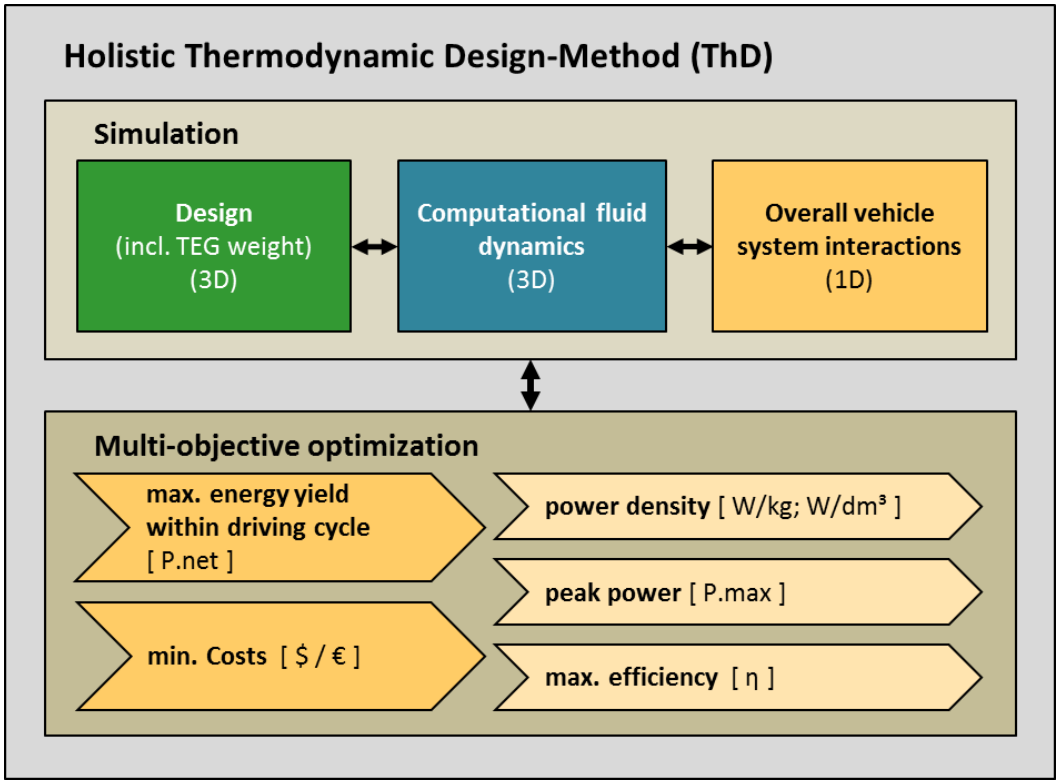
Cooling of the exhaust gas

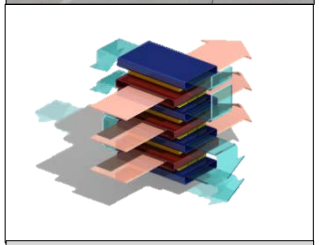
Rolling and acceleration resistance

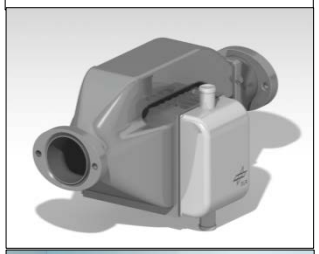
DLR

Holistic Design-Method for TEG

- Thermodynamic TEG optimization under consideration of all relevant overall vehicle system interactions (1D)
- CFD simulation (3D) in combination with design data e.g. the TEG weight
- Multi-objectiv optimization to find the best design within targets conflicts







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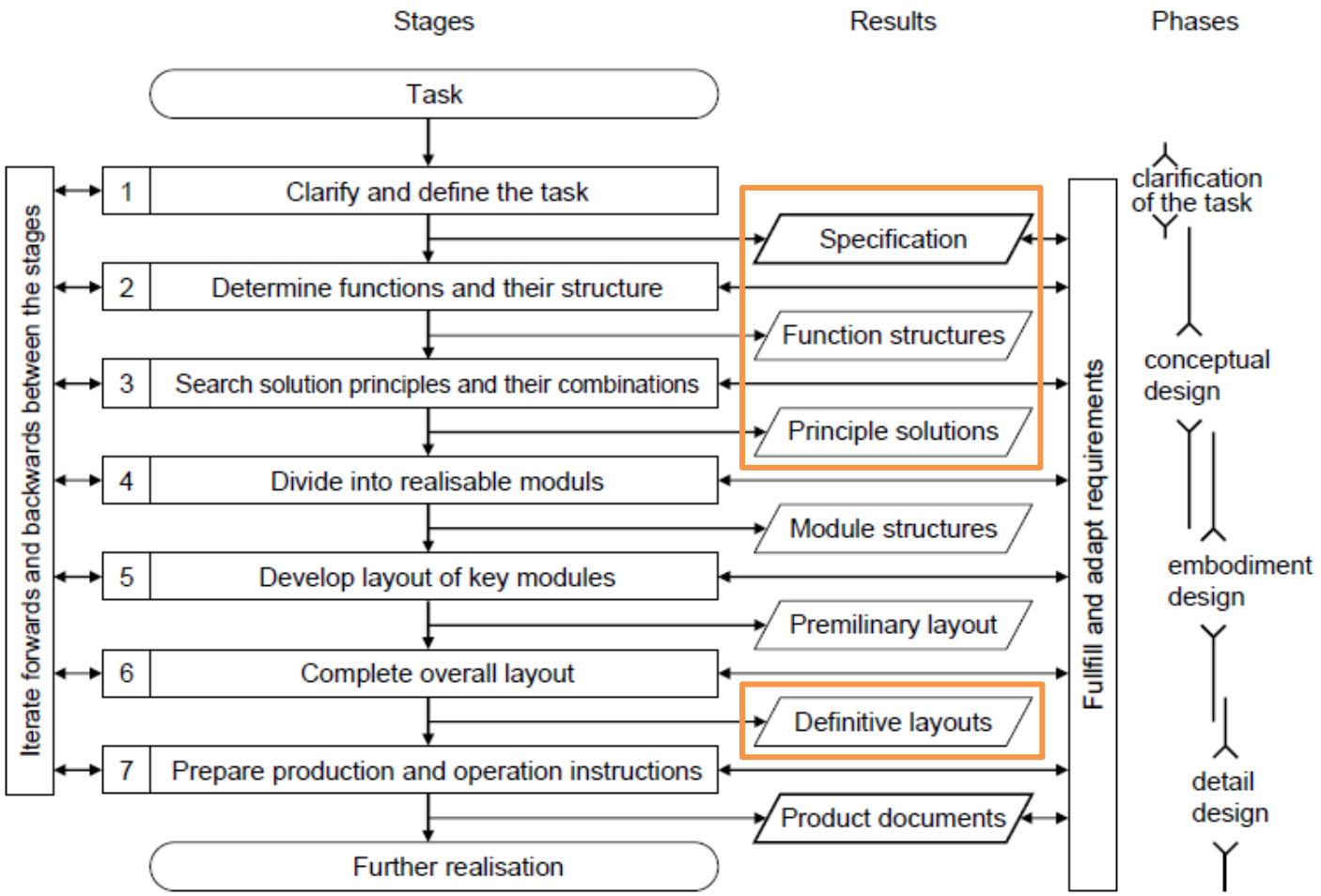
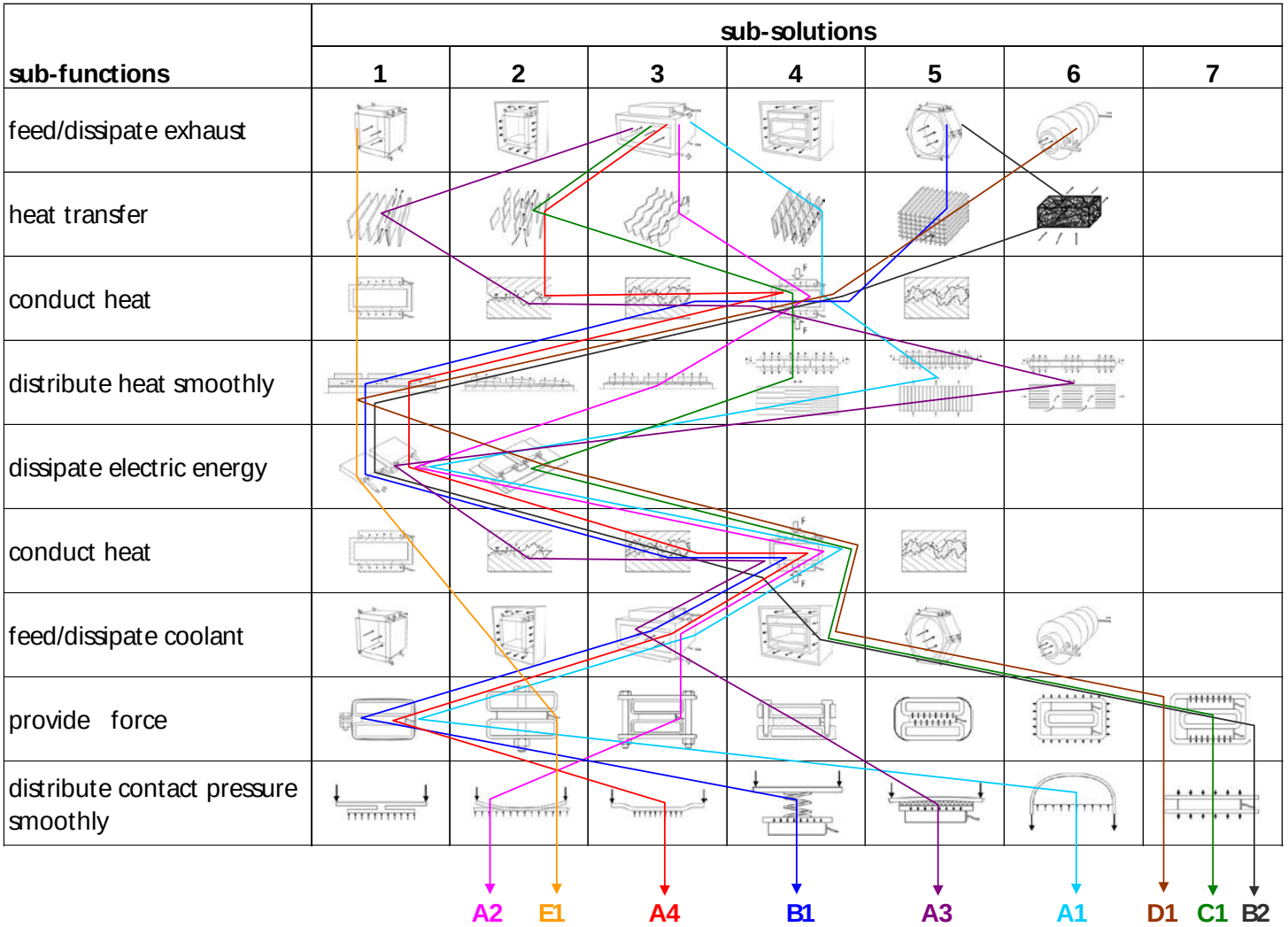
Procedural method

VDI Guideline 2221



TEG concept development – Principle-solutions

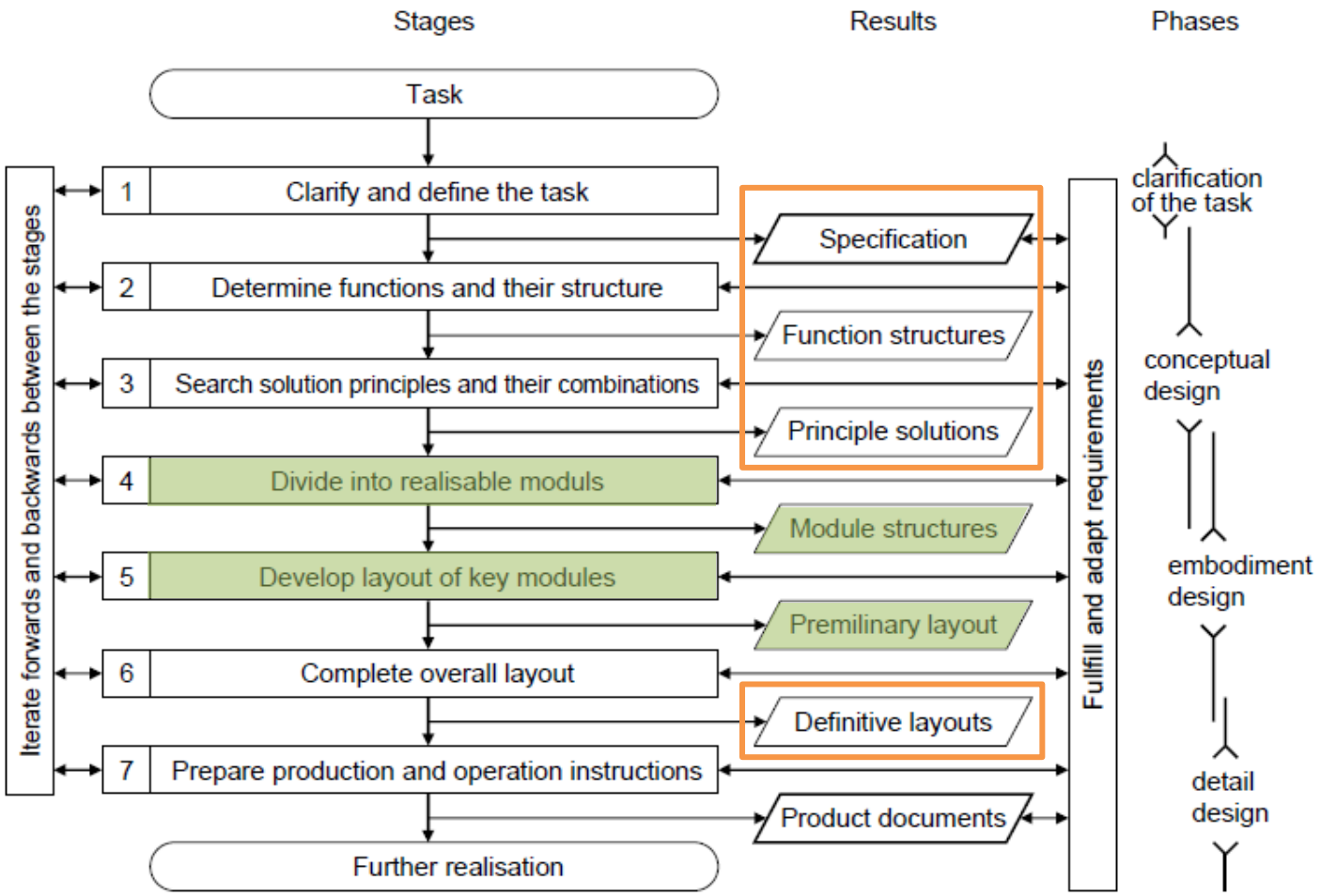


1)

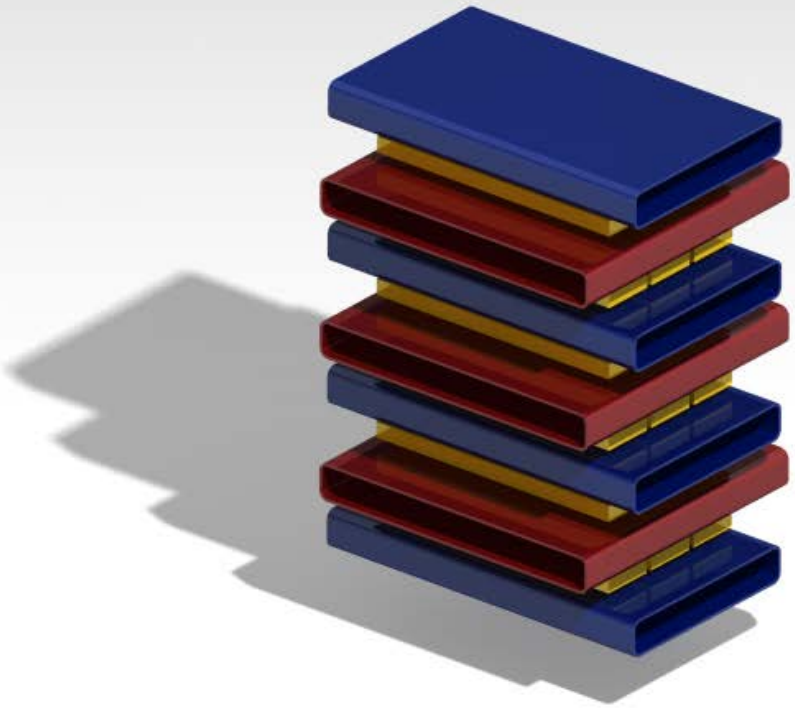
1) Kober, M. ; Häfele, C. ; Friedrich, H. E. (2012) Methodical Concept Development of Automotive Thermoelectric Generators (TEG) 3. International Conference 'Thermoelecrics goes Automotive', 2012, Berlin, Deutschland.

Procedural method

VDI Guideline 2221



Preliminary layout of the modular structure as cross-flow heat exchanger

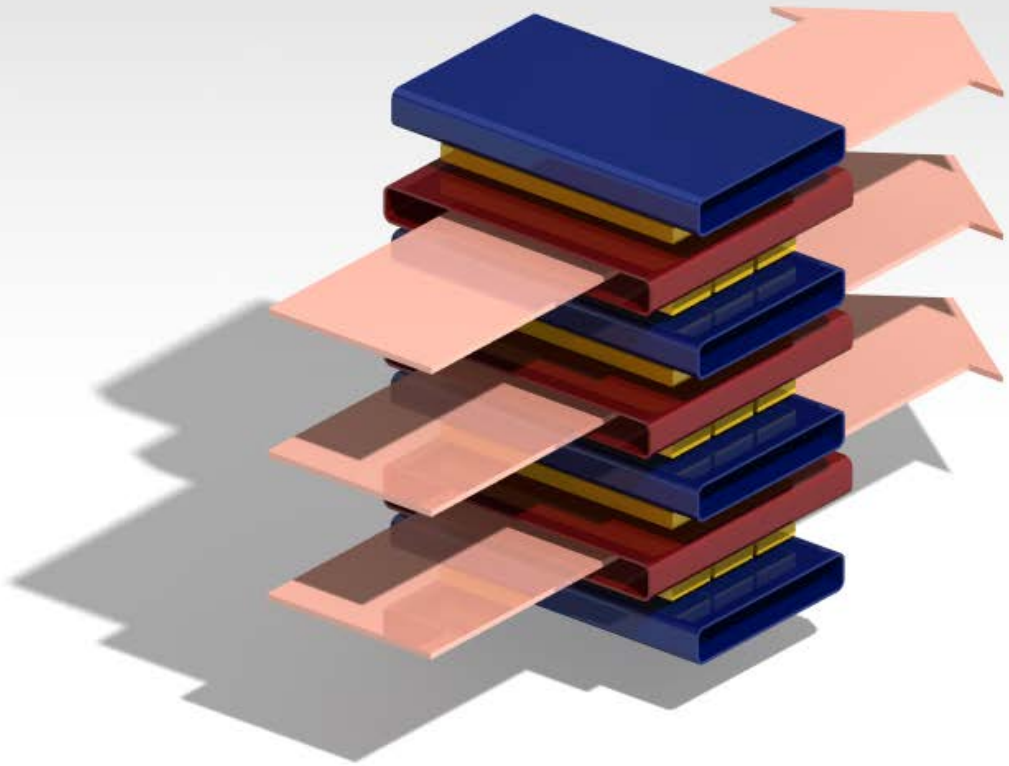


Coolant
heat exchanger

Thermoelectric
module

Hot gas
heat exchanger

Preliminary layout of the modular structure as cross-flow heat exchanger



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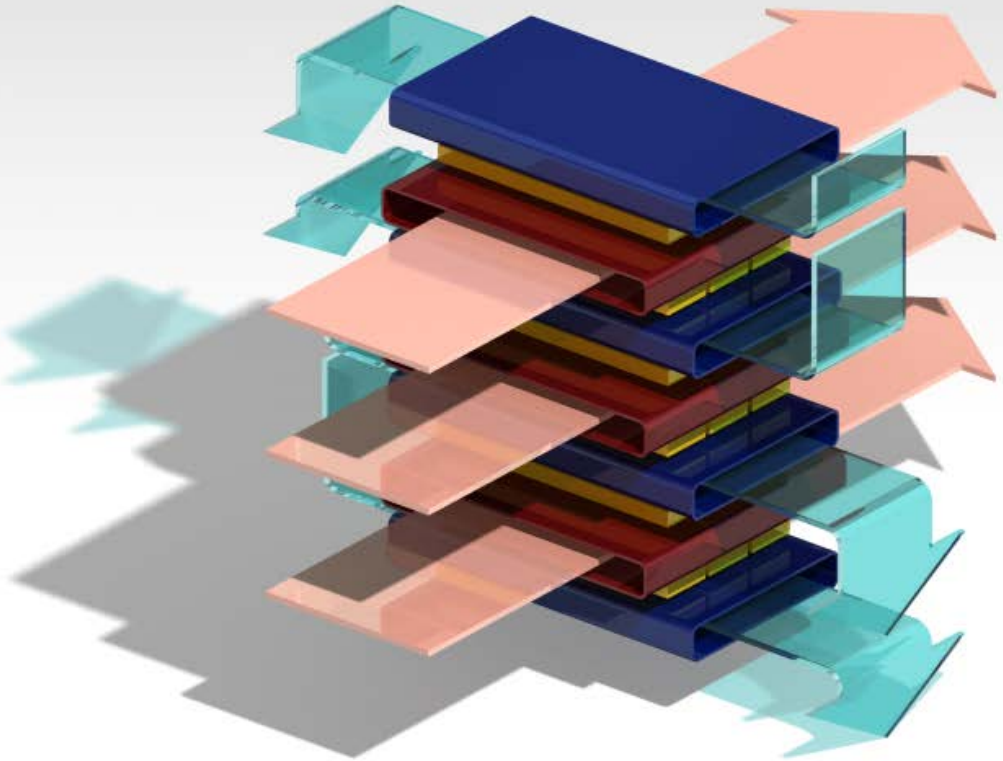
Preliminary layout of the modular structure as cross-flow heat exchanger



Coolant
heat exchanger

Thermoelectric
module

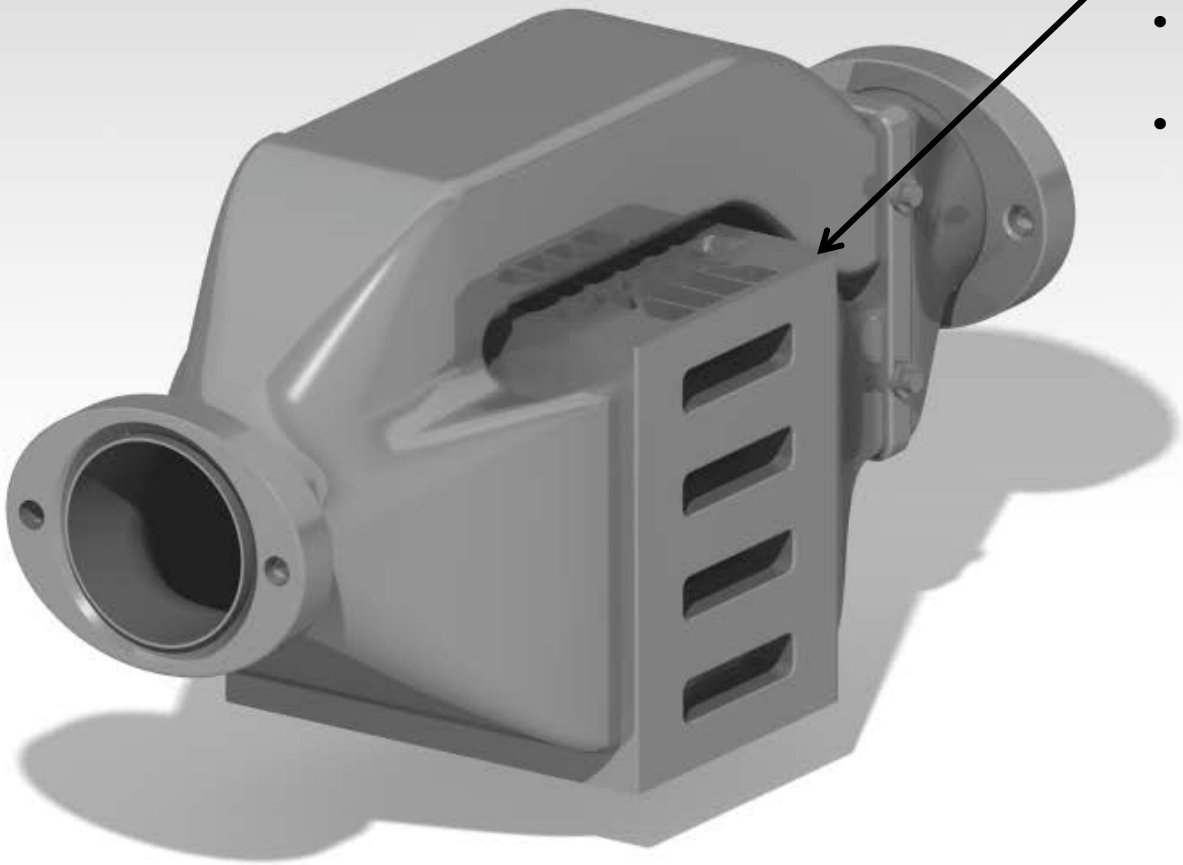
Hot gas
heat exchanger

Hot gas

Coolant

Definitive layout

Highly integrated TEG-Design including the cross-flow heat exchanger

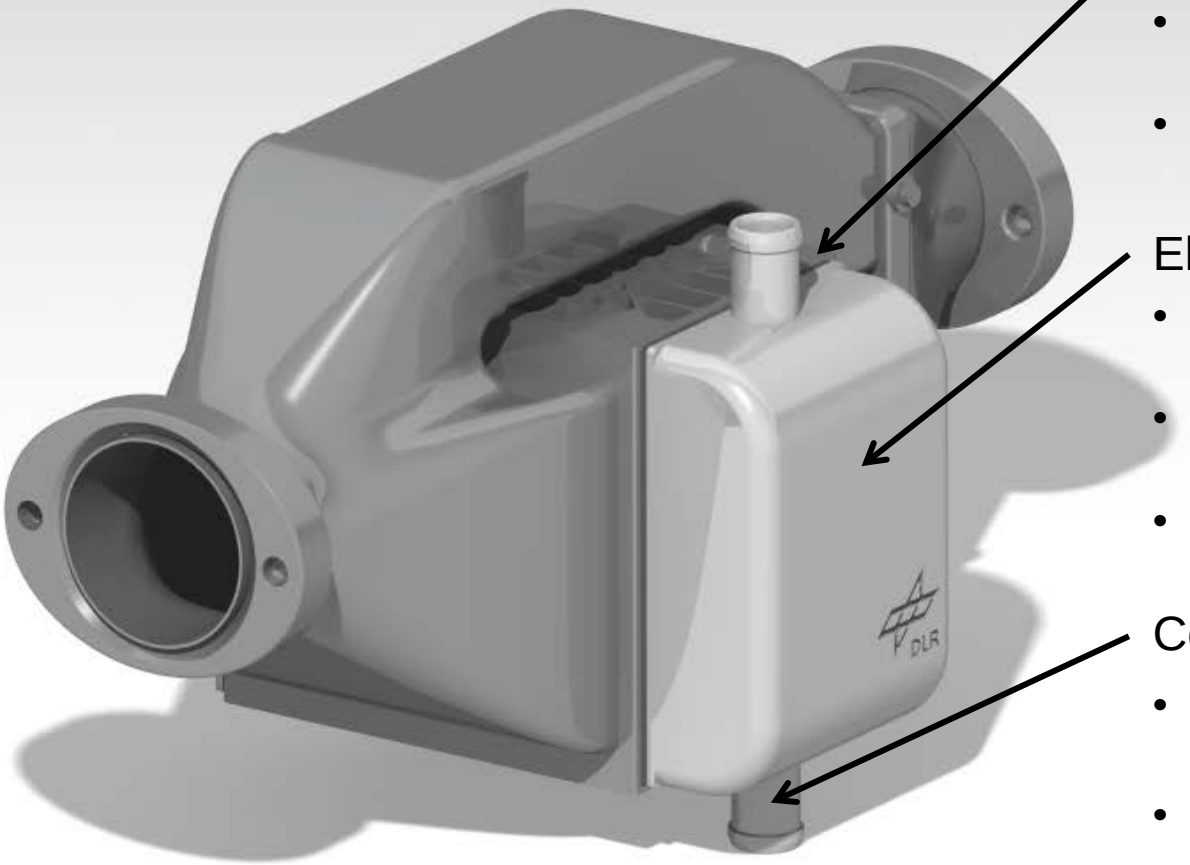


TEG-housing

- Protection against external influences
- Protective atmosphere (protective gas / vacuum)

Definitive layout

Highly integrated TEG-Design including the cross-flow heat exchanger



TEG-housing

- Protection against external influences
- Protective atmosphere (protective gas / vacuum)

Electronics

- Function integrated cooling of the electronics
- Electrical conversion inside the protective atmosphere
- Electrical plug at a higher voltage level

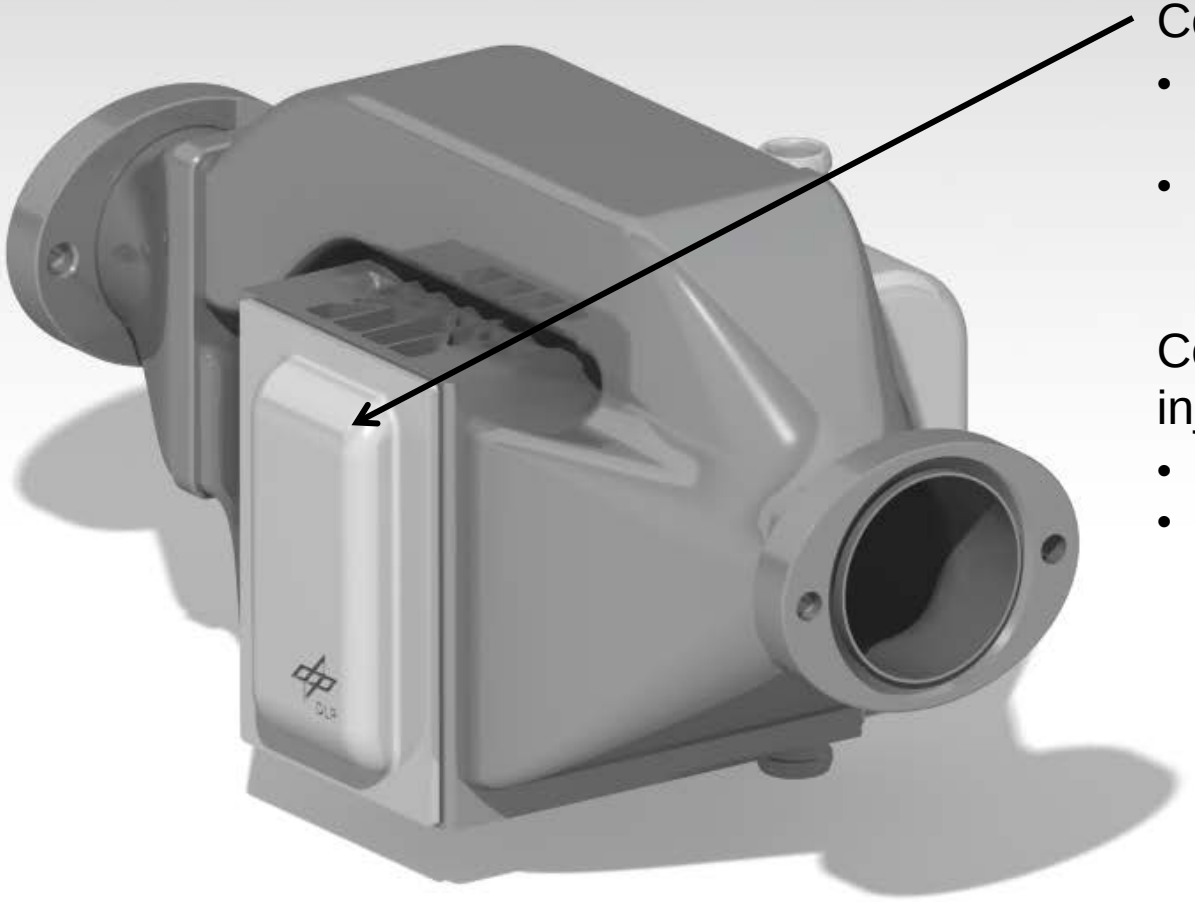
Coolant circulation system

- Function integrated in the TEG-housing
- highly integrated cross-flow heat exchanger

DLR

Definitive layout

Highly integrated TEG-Design including the cross-flow heat exchanger

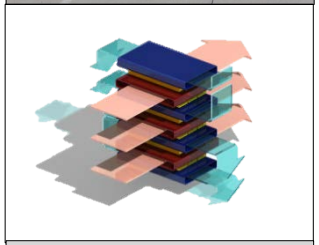


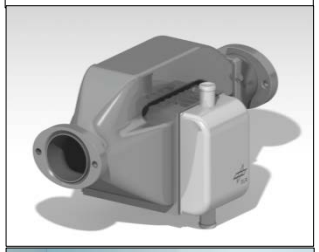
Coolant circulation system

- Function integrated coolant redirection
- Coolant heat exchanger: 2x parallel and 2x in series

Coolant guiding made from injection molding plastic

- lightness
- low cost





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Simulative results
Characteristics of the optimized TEG

TEG:

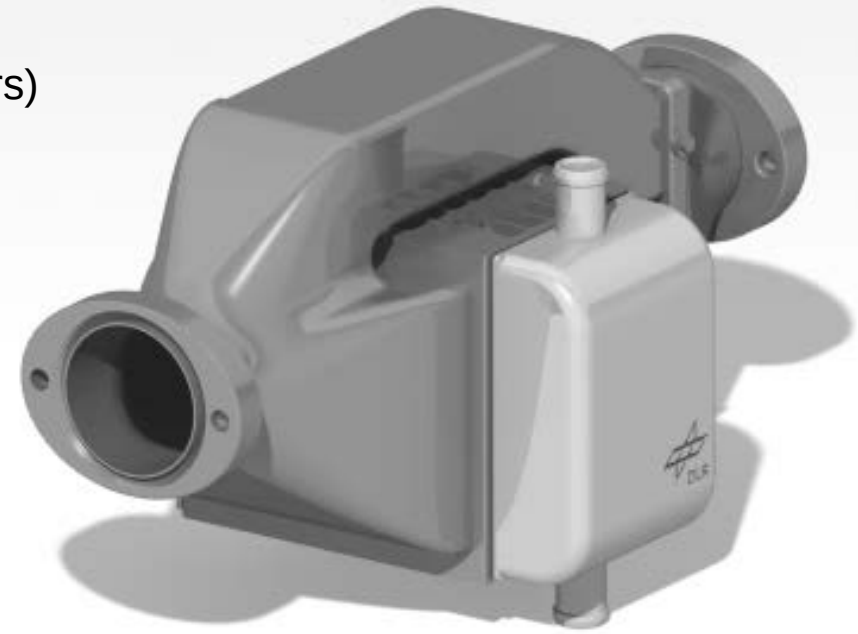
- weight < 8 kg (without bypass)
- volume < 3 dm³ (without bypass and diffusers)
- el. peak power > 400 W
- el. power at Design-Point (low load) > 160 W

Power density TEG:

- gravimetric power density > 50 W/kg
- volumetric power density > 130 W/dm³

Thermoelectric Module (TEM):

- Material class: Skutterudite [1)]
- Efficiency: 7,9% @ ΔT=480 K [1)]



This results represent the actual world highest power density for automotive TEG.

1) Kober, Martin und Heber, Lars und Heuer, Jana und Rinderknecht, Frank und König, Jan und Friedrich, Horst E. (2015) RExTEG Neuartiger Thermoelektrischer Generator zur Steigerung der Effizienz von Hybrid- und Range Extender Fahrzeugen

Results of Current Projects

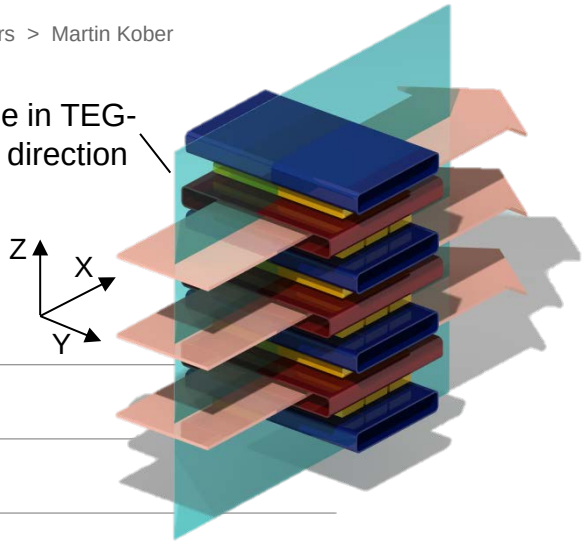
Measured Results – Validation of Simulation

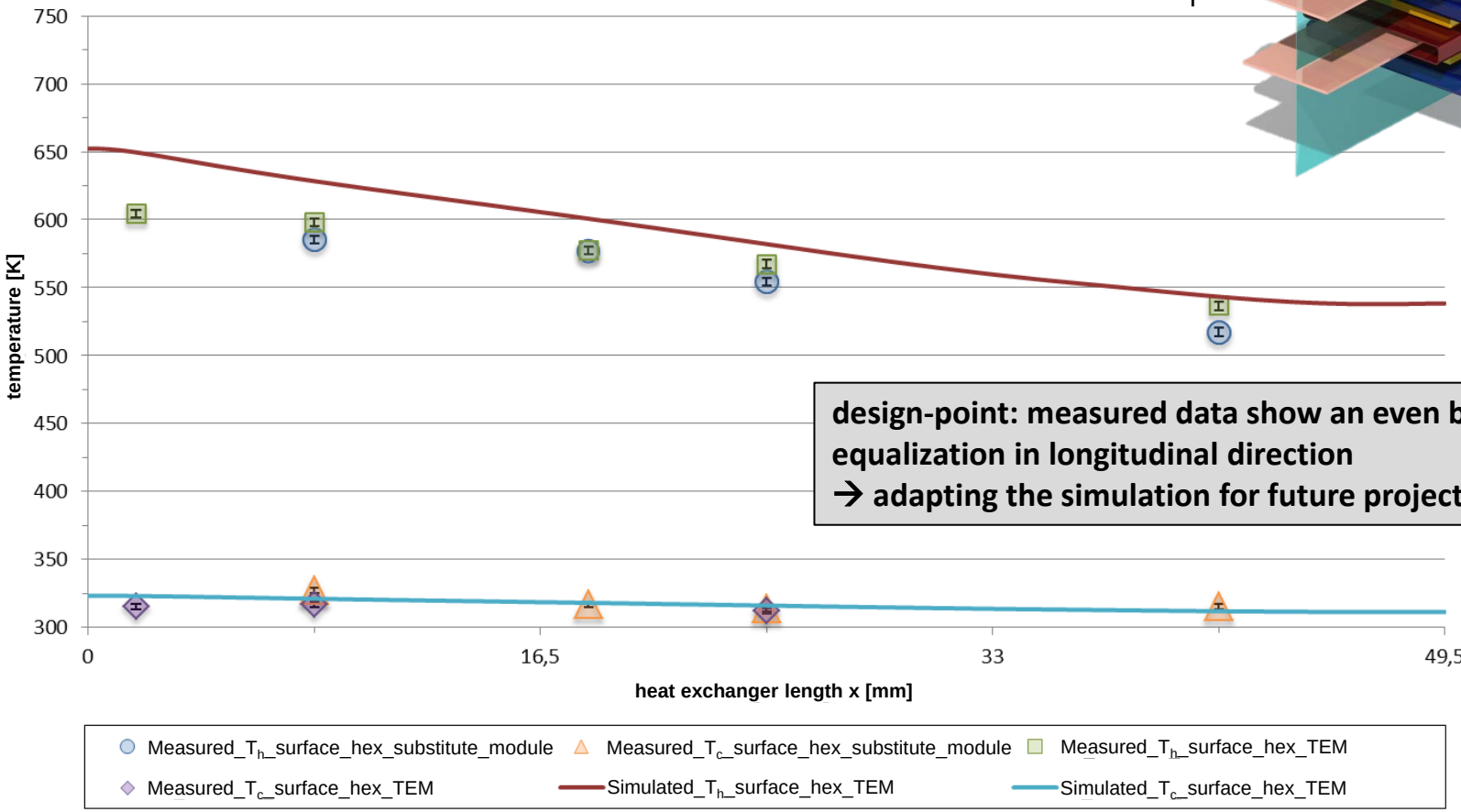
- Target value: < 8kg
  - incl. electronics (not implemented in project)
  - excl. bypass
  - excl. measurement equipment

- Functional prototype: 8,3 kg
  - measurement equipment: - 2,1 kg
  - electronics (assumption): + <1,5 kg

  → achieved weight <7,7 kg

Measurement results
validation of simulation - design-point

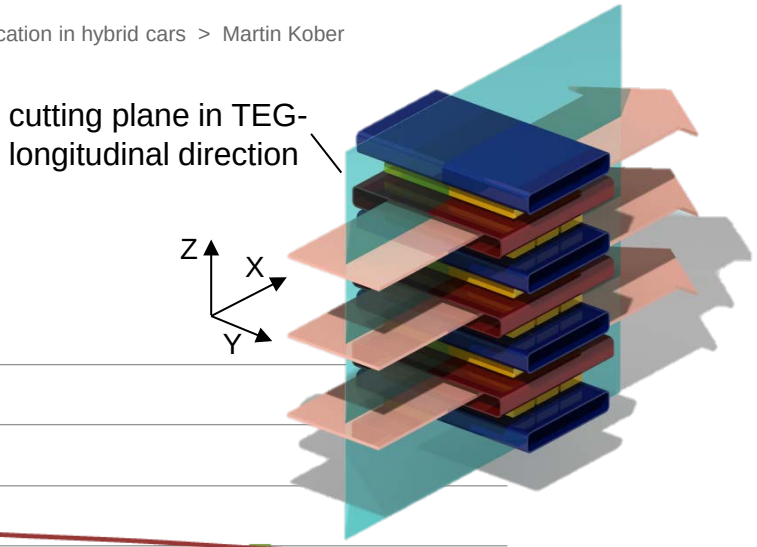


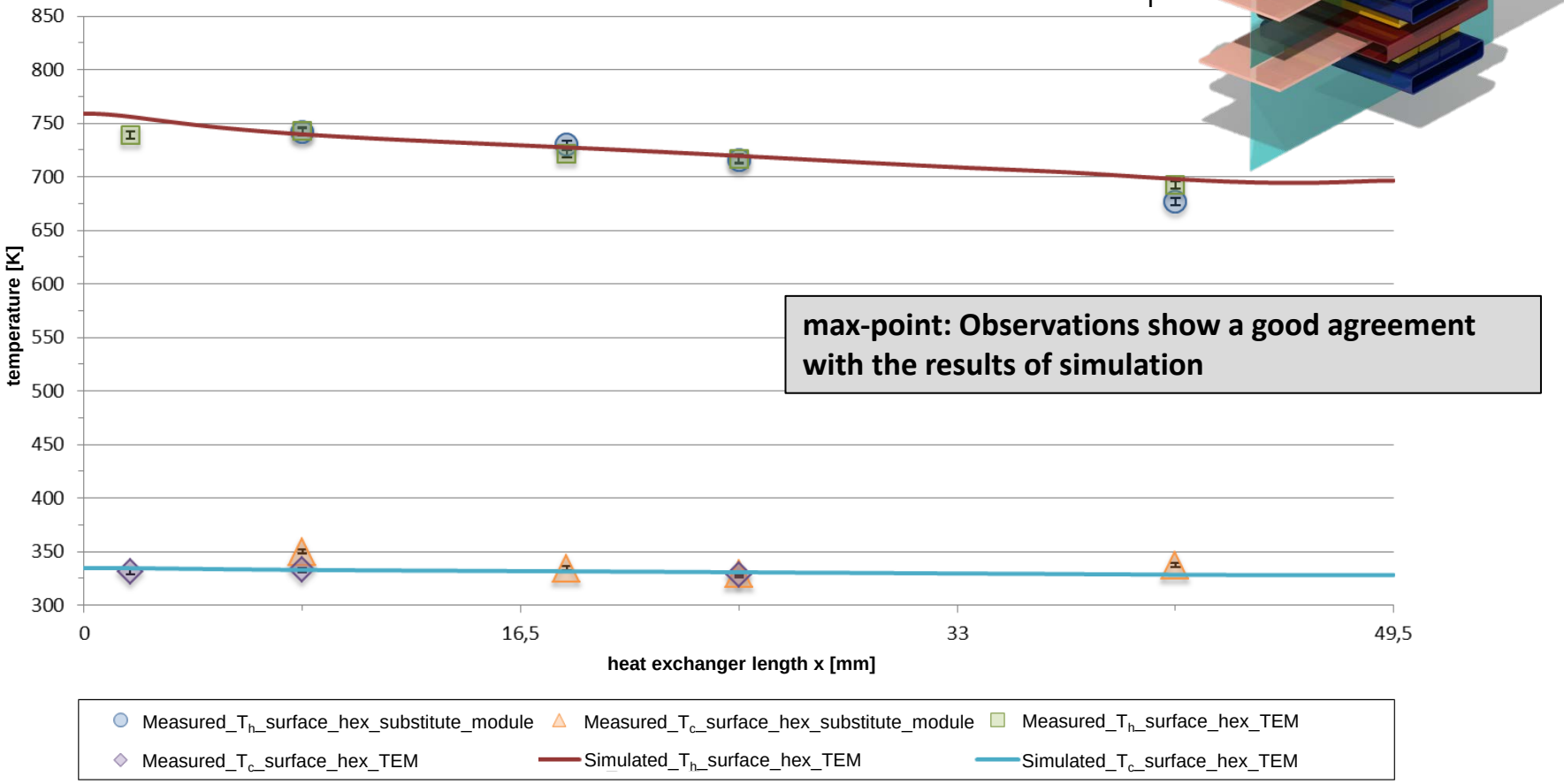


design-point: measured data show an even better equalization in longitudinal direction
→ adapting the simulation for future projects

Comparison of measurement and CFD simulation of the hot side (Th) and cold side (Tc) at the measurement point 1 - design-point

Measurement results
validation of simulation - max-point





max-point: Observations show a good agreement with the results of simulation

Comparison of measurement and CFD simulation of the hot side (Th) and cold side (Tc) at the measurement point 9 - max-point

Impressions

Summary

- Procedure to increase the power density
- Presentation of a new holistic design method
- Presentation of highly integrated TEG-construction
- Comparison of measurement and simulation results

Projekt RExTEG

Acknowledgement

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