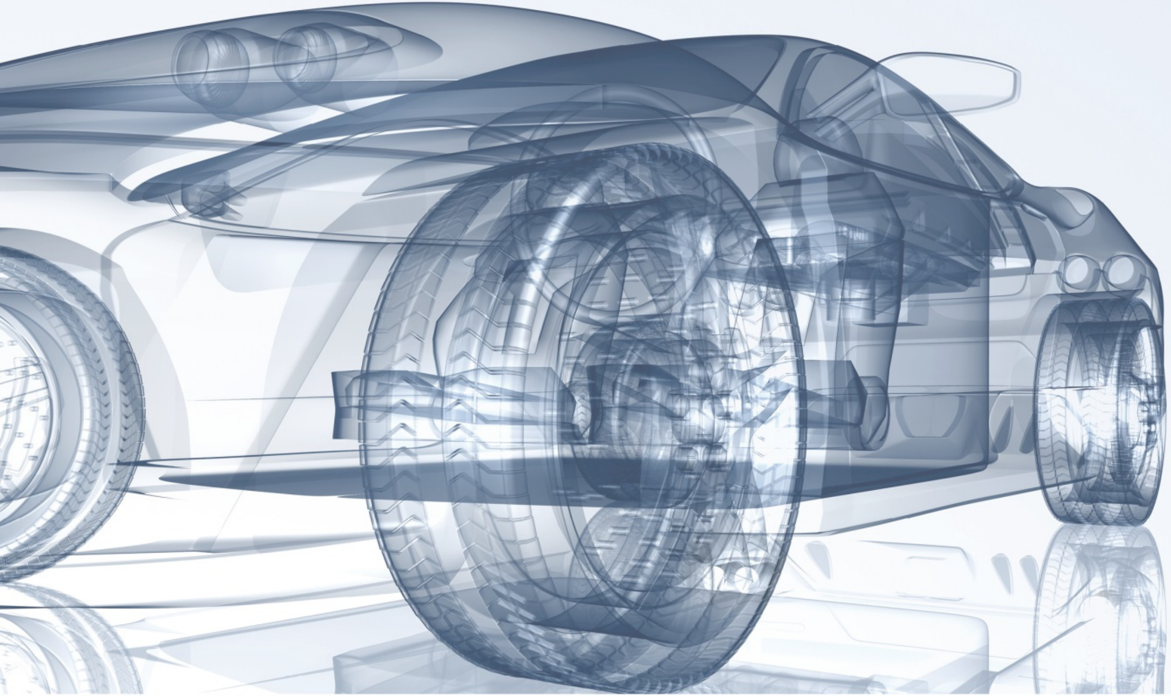
evs 30

# The 30th International Electric Vehicle Symposium & Exhibition



**October 9–11, 2017**

Messe Stuttgart, Germany

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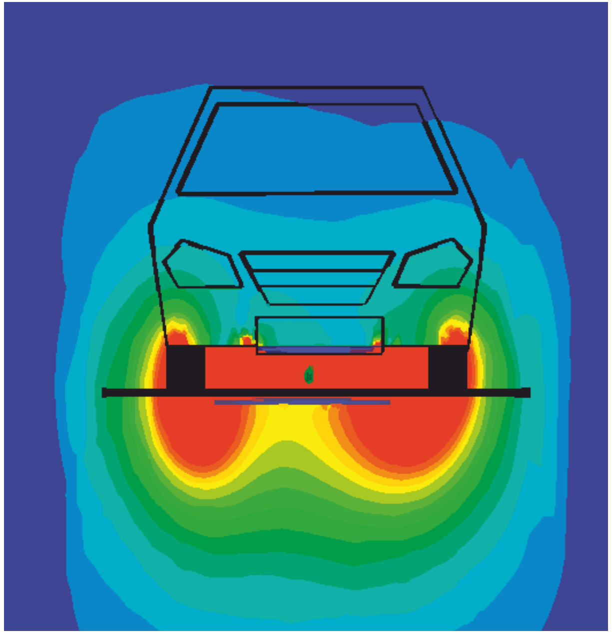
# Coil Topologies for Inductive Power Transfer in Automotive Applications

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[1] Berührungsloses, induktives Laden in ÖPNV und Individualverkehr, Ingenieurspiegel 2014

# Motivation

- Various coil topologies are applied in IPT systems
- ? Choice of optimal topology for selected automotive applications?
- ? Optimal design of these topologies

- ! Selection of topologies for Minicars and SUVs
- ! Optimized coil systems
  - ! Light-weight and compact
  - ! Low magnetic stray field (ICNIRP 2010)
  - ! High efficiency, also in case of lateral misalignment

# Agenda

- **Automotive Applications**
  - Characteristics of Minicars and SUVs
  - Derivation of Requirements on the Coil System
- State of the Art of Current Topologies for IPT Systems
  - Selection of Coils
  - Characteristics of the Coils
- Optimization
  - Procedure
  - Results
- Validation and Verification
- Conclusion

# 1. Automotive Applications



| Minicars | SUVs |
|---|---|
| ▪ small<br>▪ lightweight<br>▪ inexpensive<br>▪ short distances | ▪ large<br>▪ higher ground clearance<br>▪ sales are growing |
| ▪ top-selling 2015 in Germany[2]:<br>▪ Hyundai i10<br>▪ Smart ForTwo<br>▪ Opel Adam<br>▪ Fiat 500<br>▪ VW Up | ▪ top-selling 2015 in Germany[2]:<br>▪ Hyundai ix35<br>▪ Nissan Qashqai<br>▪ Ford Kuga<br>▪ Opel Mokka<br>▪ VW Tiguan |

[2] German Federal Motor Transport Authority

# 1. Automotive Applications



| Requirements | Based on | Minicar | SUV |
|---|---|---|---|
| Maximum coil size | Installation space available | 1 m x 1 m | 1 m x 1 m |
| Air gap | Demanded ground clearance | 110 mm | 200 mm |
| Magnetic stray field | Requirements ICNIRP 2010 | 27 µT @ 850 mm | 27 µT @ 950 mm |
| Max. secondary current | Current densities | 120 A | 240 A |
| Positioning tolerance | Standardization requirements, IEC 2014 | R = 150 mm | R = 150 mm |
| Power to be transmitted | | 22 kW (WPT3) | 50 kW (WPT4) |
| Efficiency | | > 80 % | > 80 % |
| Frequency | | 85 kHz | 85 kHz |

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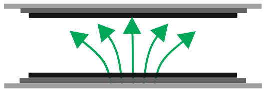
# 2. State of the Art of Current Topologies



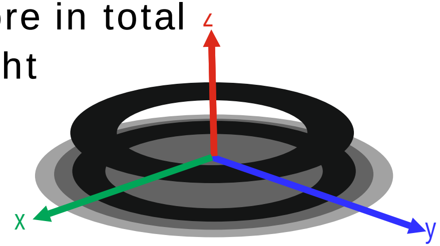
- Which topology for the two cases of application
- Strengths and weaknesses of 16 topologies already analyzed [3,4]

## Coil for Minicars

- unpolarized coupler
  - inexpensive
  - comparatively simple
  - for small installation space

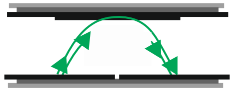


- circular, planar coil (CP)
  - good score in total
  - low weight

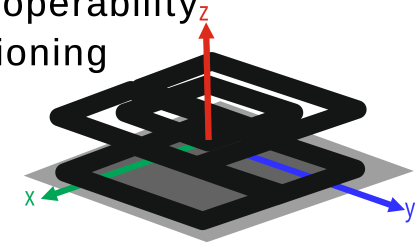



## Coil for SUVs

- polarized coupler
  - large air gaps
  - high power transfer
  - low magnetic stray field

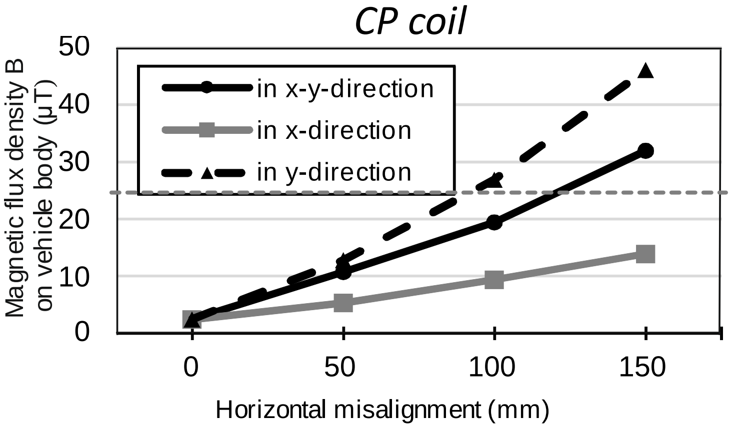


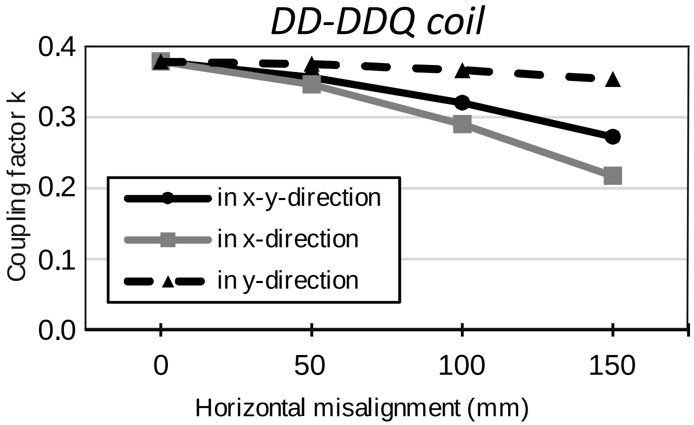
- combination DD & DDQ (DD-DDQ)
  - good interoperability
  - high positioning tolerance




[3] K. Knaisch and P. Gratzfeld, "*Comparison of magnetic couplers for inductive electric vehicle charging [..]*"
[4] K. Knaisch, M. Springmann, and P. Gratzfeld, "*Comparison of Coil Topologies for IPT under the Influence of Ferrite and Aluminum*"

# 2. State of the Art of Current Topologies Characteristics




- ICNIRP requirements can be met for some cases
- both topologies operate with the highest performance at any time
- only a transferred power of 80 % of the nominal power is required in case of maximum offset

→ There is some room left for an optimization of the system
→ Analyze possible reduction of the secondary coil system size

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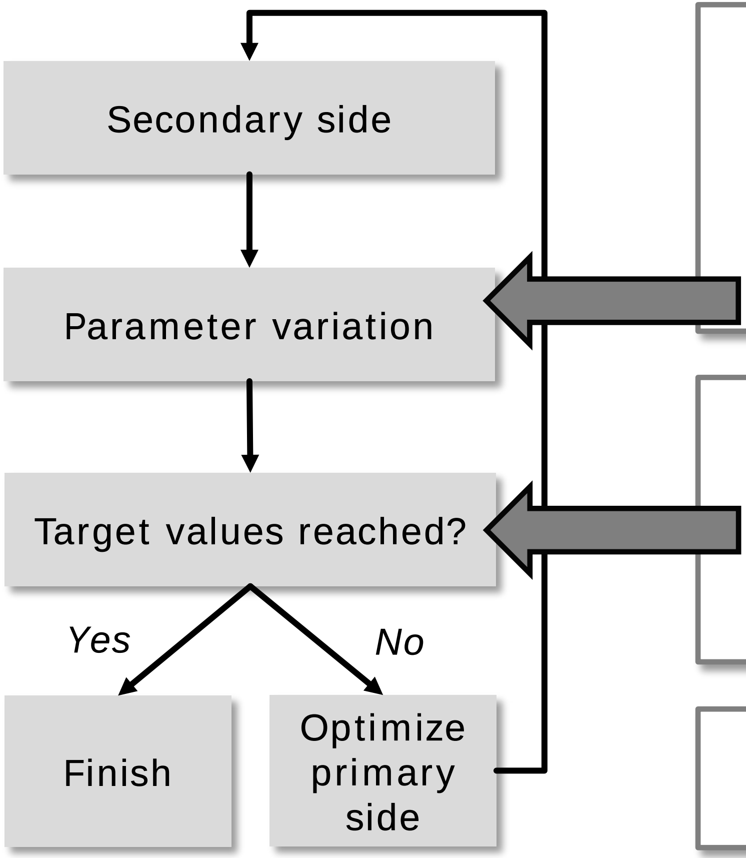
# 3. Optimization






- Ø Coil
- Size quadrature coil (if any)
- Ø Ferrite and Aluminum accordingly
- Number of turns
- Geometry Ferrite Bars
  - Number, Length, Width

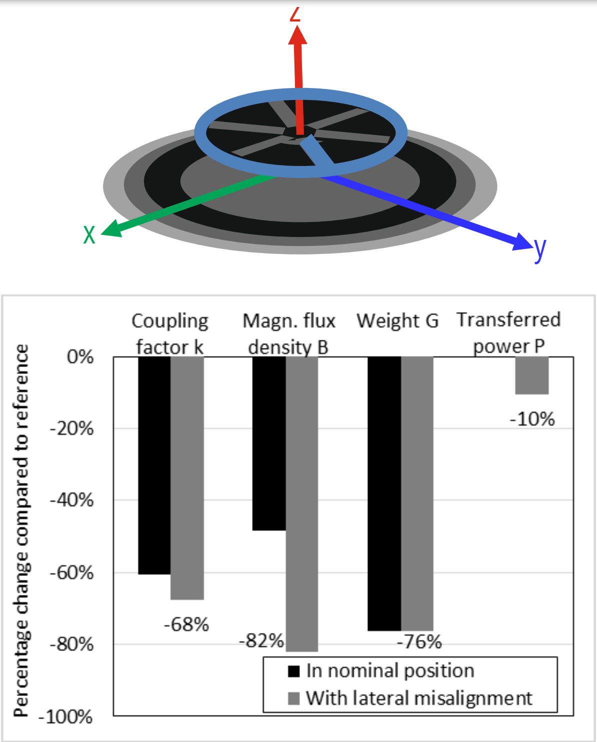
| | |
|---|---|
| Weight: | min |
| Coupling factor: | max |
| Magnetic stray field: | < 27 µT |
| Transmitted Power: | 22 kW / 50 kW |
| Efficiency: | > 80 % |

All simulations:
in worst case of lateral misalignment

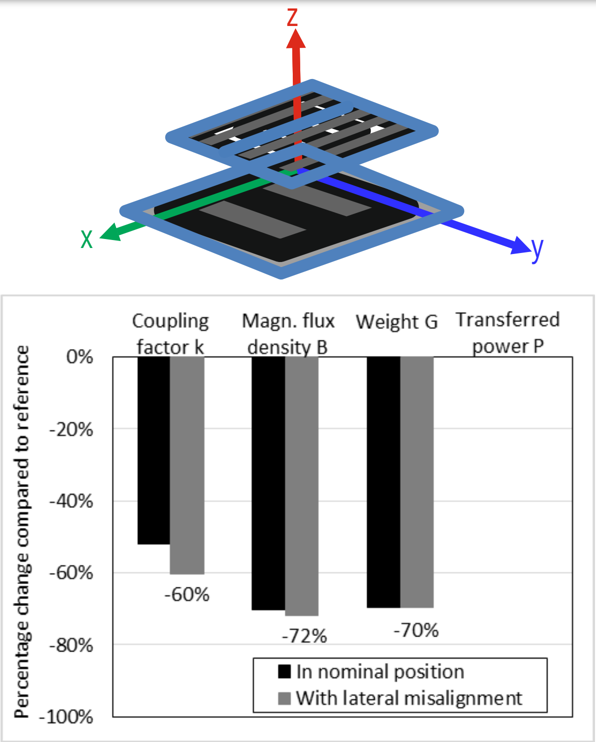
# 3. Optimization



## CP coil (secondary)




## DD-DDQ coil (primary & secondary)



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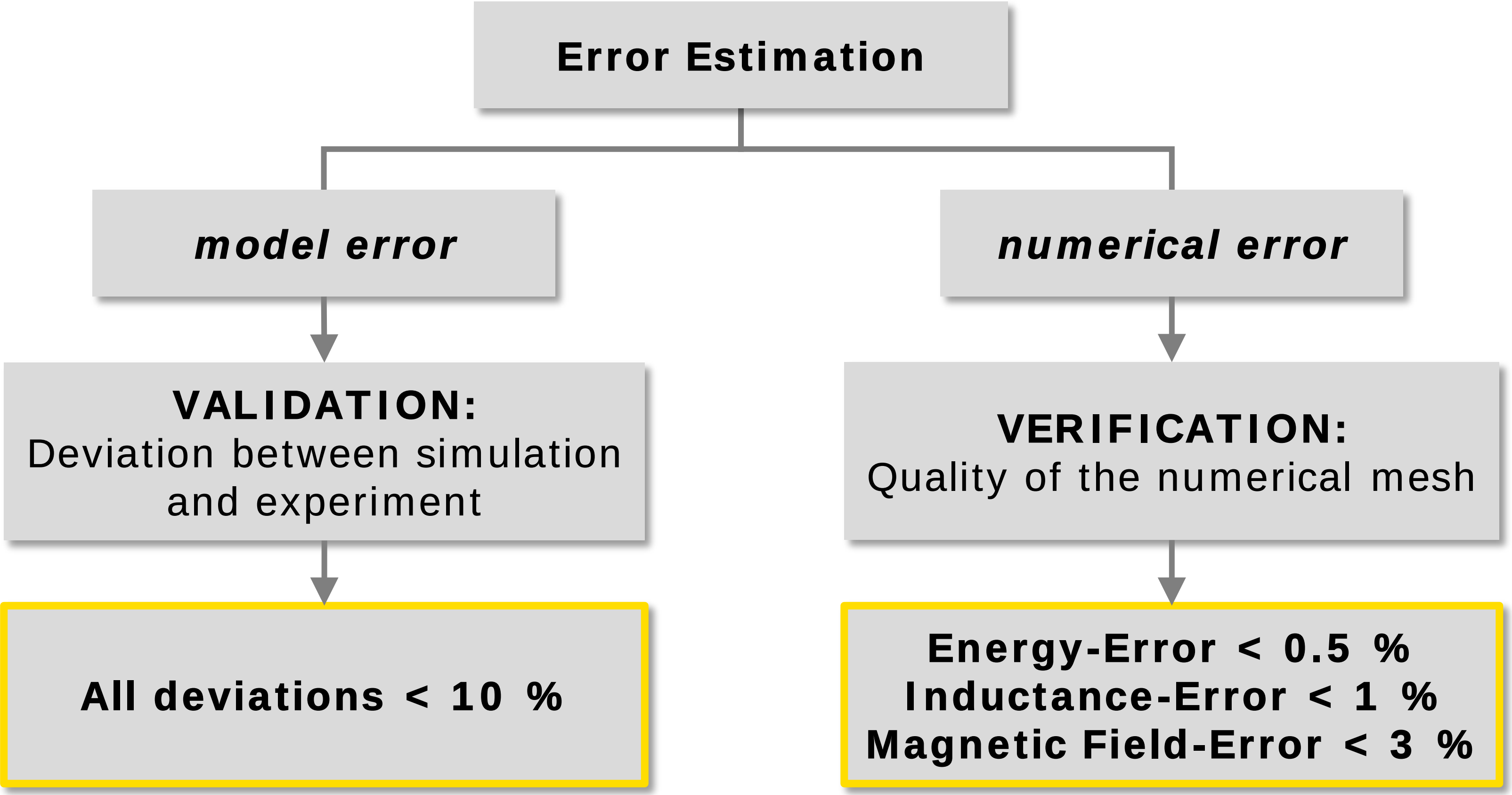
# 4. Verification and Validation



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# 5. Conclusion

- Presentation of two automotive applications: Minicars & SUV
- Derivation of requirements on the coil system based on
  - Characteristics automotive applications
  - Standardization activities
  - ICNIRP Guidelines
- Choice of optimal topology for Minicar & SUV: CP & DD-DDQ
- Optimization of both topologies through parameter variations
  - Reduction in weight (76 % / 70 %)
  - Reduction of magnetic stray field (82 % / 72 % )
  - Fulfillment of all requirements
- Validated and verified simulation models

# Thank you for your attention

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# Sources


1. R. Arnold, K. Knaisch and P. Gratzfeld, „*Berührungsloses induktives Laden in ÖPNV und Individualverkehr,*“ Ingenieurspiegel Bd 2, 2014
2. German Federal Motor Transport Authority, “*New Registrations of Passenger Cars in 2015 by Segments and Series of Models: Neuzulassungen von Personenkraftwagen im Dezember 2015 nach Segmenten und Modellreihen,*” 2015.
3. K. Knaisch and P. Gratzfeld, “*Comparison of magnetic couplers for inductive electric vehicle charging using accurate numerical simulation and statistical methods,*” International Electric Drives Production Conference (EDPC), pp. 1–10, 2015.
4. K. Knaisch, M. Springmann, and P. Gratzfeld, “*Comparison of Coil Topologies for Inductive Power Transfer under the Influence of Ferrite and Aluminum,*” Ecological Vehicles and Renewable Energies Conference (EVER), pp. 1–9, 2016.

# Dimensions of the Reference Coils

| | Minicars / CP coil | SUV / DD-DDQ-coil |
|---|---|---|
| Size of coil system [mm] | Ø 800 | 900 × 900 |
| Cross section of coil [mm²] | 50 | 100 |
| Number of turns [ ] | 5 | 5 |
| Distance between windings [mm] | 20 | 10 |
| Distance between sub-coils [mm] | - | 10 |
| Size of quadrature coil [mm] | - | 500 × 500 |
| Number of turns quadrature [ ] | - | 3 |
| Ferrite size [mm] | Ø 900 | 800 × 800 |
| Ferrite height [mm] | 5 | 5 |
| Aluminum size [mm] | Ø 1000 | 1000 × 1000 |
| Aluminum height [mm] | 5 | 5 |
| Vehicle underbody [mm] | Ø 1500 | Ø 1600 |
| Air gap [mm] | 110 | 200 |
| Lateral misalignment in x-y-direction | 150 | 150 |

# Dimensions of the Optimized Coils

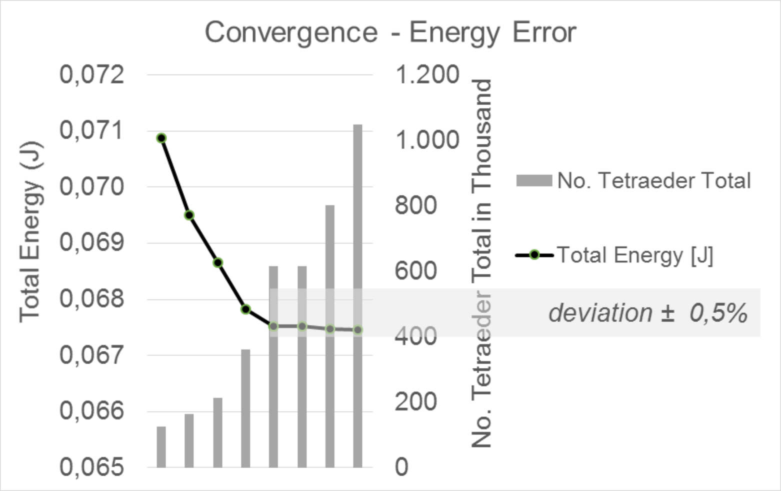
| | Minicars / CP coil | | SUV / DD-DDQ-coil | |
|---|---|---|---|---|
| | Primary | Secondary | Primary | Secondary |
| Size of coil system [mm] | Ø 800 | Ø 550 | 600 × 600 | 600 × 450 |
| Cross section of coil [mm²] | 50 | 110 | 100 | 120 |
| Number of turns [ ] | 5 | 8 | 6 | 6 |
| Distance between windings [mm] | 20 | 20 | 10 | 10 |
| Distance between sub-coils [mm] | - | - | 10 | 10 |
| Size of quadrature coil [mm] | - | - | 500 × 500 | 200 × 300 |
| Number of turns quadrature [ ] | - | - | 3 | 2 |
| Number of ferrite bars [ ] | - | 6 | | 6 |
| Width of ferrite bars [mm] | - | 40 | | 40 |
| Ferrite size [mm] | Ø 900 | Ø 500 | 600 × 600 | 500 × 450 |
| Ferrite height [mm] | 5 | 5 | 5 | 5 |
| Aluminum size [mm] | Ø 1000 | Ø 650 | 700 × 700 | 700 × 700 |
| Aluminum height [mm] | 5 | 5 | 5 | 5 |

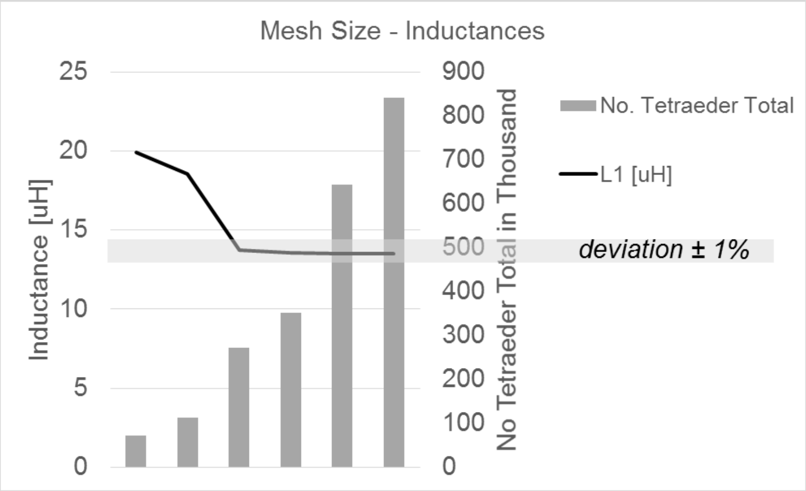
# Dimensions of the Experimental Prototype

### Simulation Model

| | | |
|---|---|---|
| Coil diameter | 510 mm | |
| Cross section of coil | 50 mm² | |
| Number of turns | 7 | |
| Distance between windings | 20 mm | |
| Ferrite | primary: | 850 mm x 850 mm x 6 mm |
| | secondary: | 570 mm x 570 mm x 4 mm |
| Aluminum | primary: | 940 mm x 940 mm x 5 mm |
| | secondary: | 600 mm x 600 mm x 5 mm |
| Vehicle underbody | Ø 1400 mm x 1 mm | |
| Variation of air gap | 120 \| 135 \| 150 mm | |
| Variation of misalignment | 0 \| 25 \| 50 \| 75 \| 100 mm | |

# Results Verification



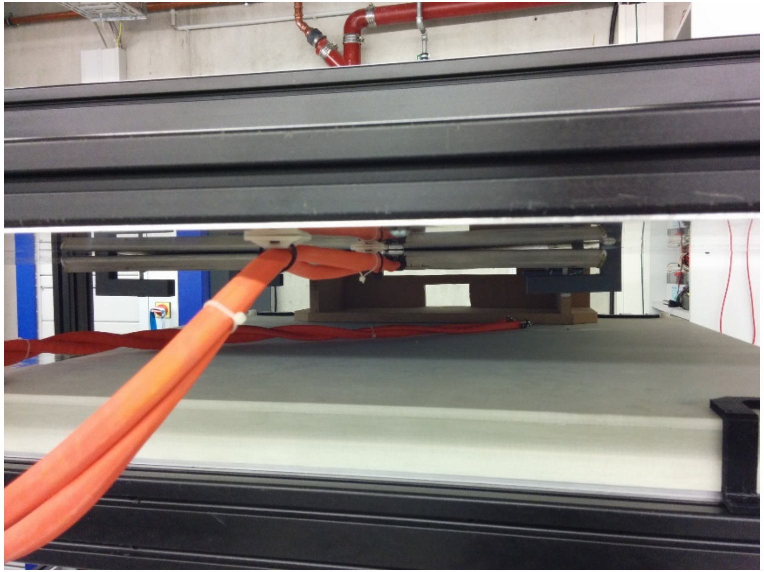




- Energy Error: < 0,5 %
- No. of Tetrahedra: > 400.000
- Max. deviation of statistical outliers of B: < 15 %
- Ø deviation of all values of B: < 3 %

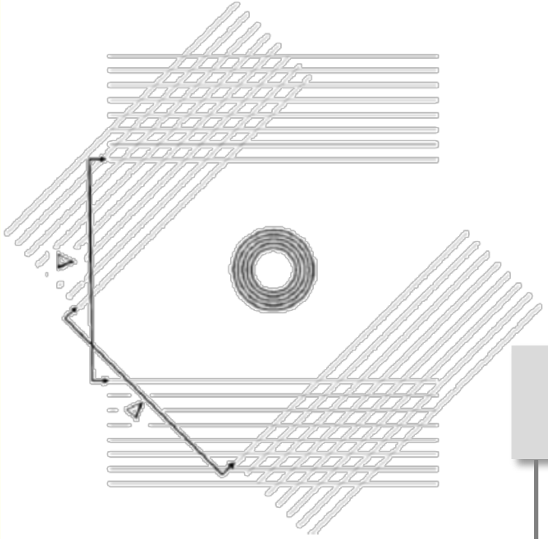
# Results Validation

## Deviation Measurement - Simulation

| | Average deviation in % | Maximum deviation in % | Standard deviation |
|---|---|---|---|
| $L_1$ | 4.22 | 5.20 | 0.97 |
| $L_2$ | -3.66 | 4.28 | 0.30 |
| k | -6.93 | 8.17 | 0.56 |



# 4. Validation and Verification



**VERIFICATION**
***numerical error***

Quality criteria for the numerical mesh

Spatial region

- center of the coils
  → *(I) convergence*
- outer area beyond the coils
  → *(III) deviation field*

Electromagnetic Quantities

- inductances
  → *(II) mesh independence*
- field quantities
  → *(III) deviation field*

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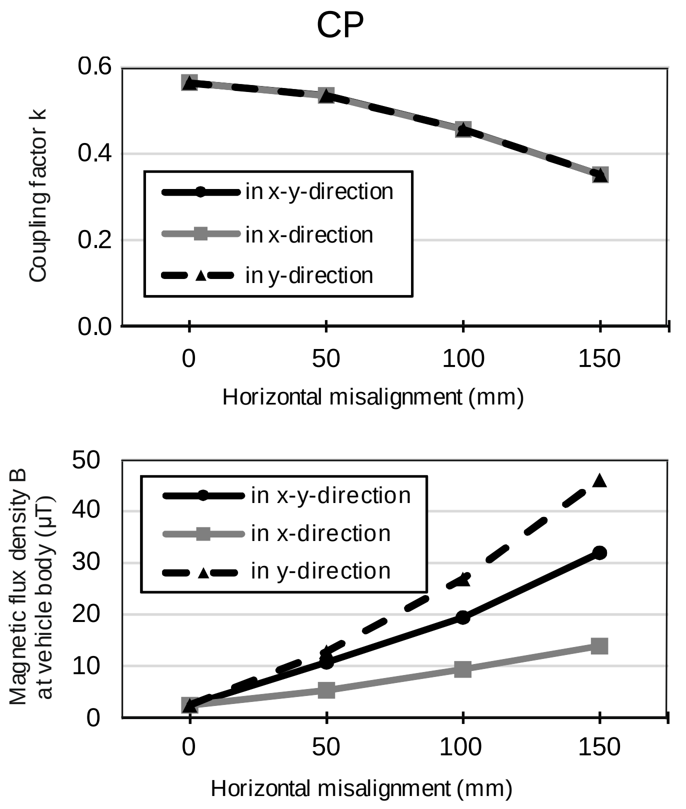


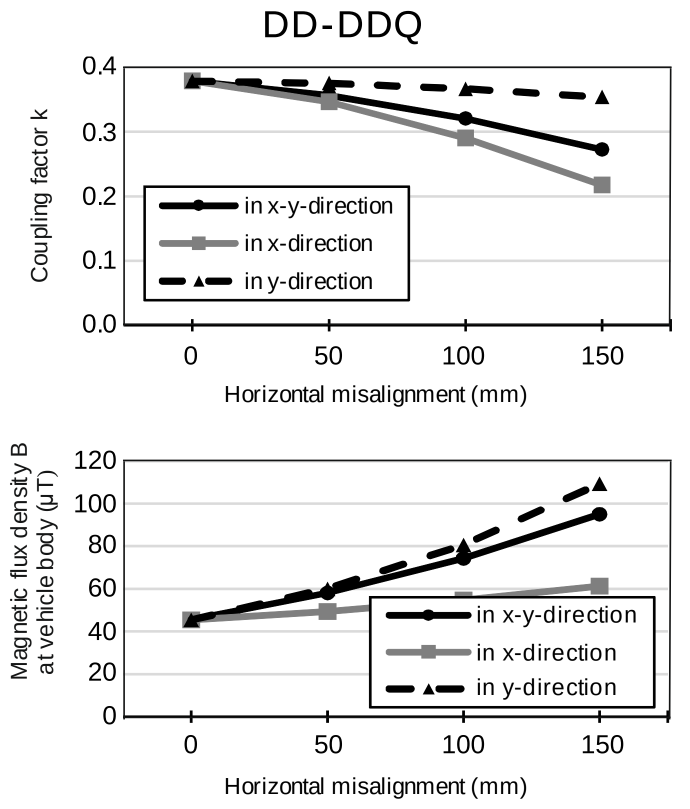

# 3. Optimization