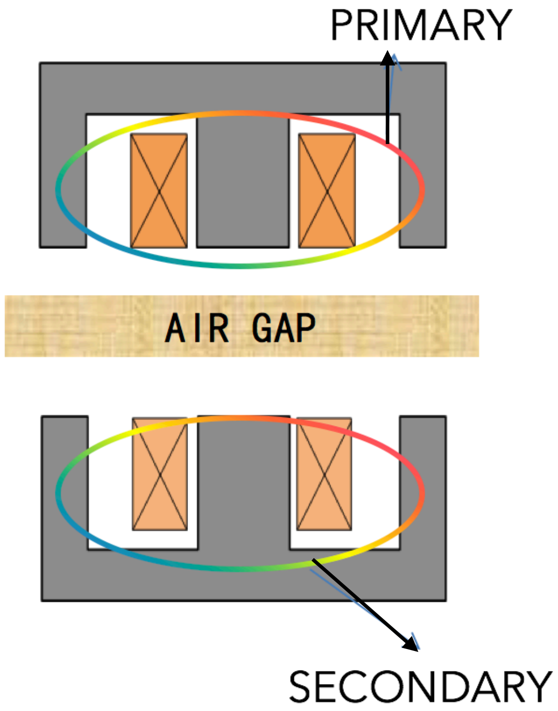
Part IV: Transformer Design

C K MICHAEL TSE
Department of Electronic and Information Engineering
Hong Kong Polytechnic University
http://cktse.eie.polyu.edu.hk

TRANSFORMER DESIGN

PART IV

Contactless Transformers



Transformers with low coupling coefficients

- Large leakage inductance
- Small magnetizing inductance

Design Issues

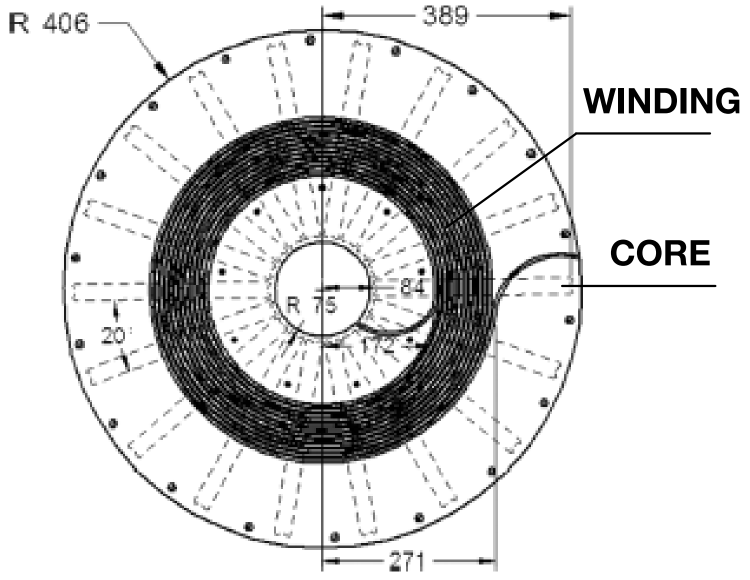
Raise coupling coefficient

Reduce effect of misalignment

Increase Q (less loss)

Reduce volume and size

EMI issues



Circular Pad Transformer

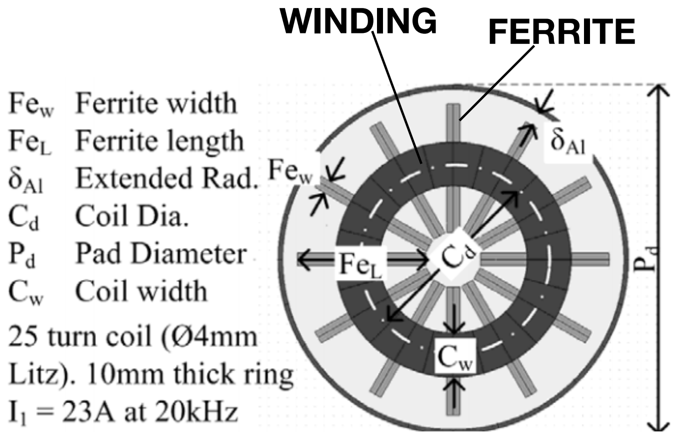
Power Pad (Auckland)

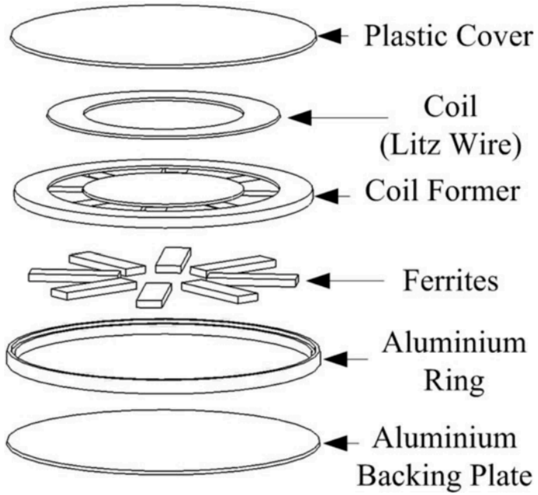
Transformers with stripped cores

- Coupling coefficient is not seriously affected
- Volume is dramatically reduced

Design Issues

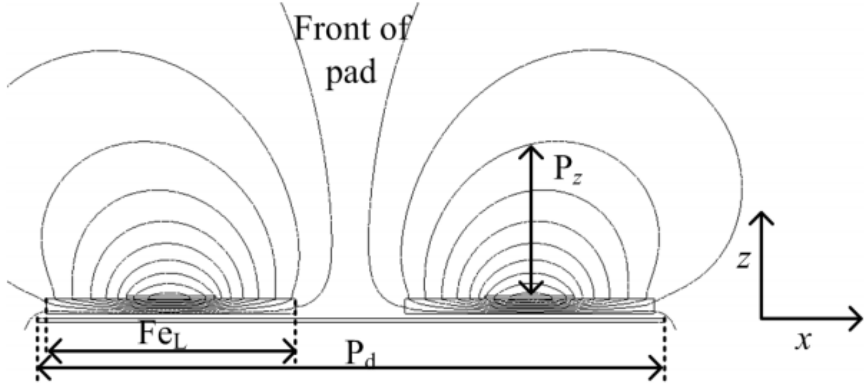
- Winding distributions affect the power transfer capacity measured by P_{su} which is the uncompensated power ($P_{su} = V_{oc}I_{sc}$). So, $P_{out} = P_{su}Q$.
- When [core diameter]/[pad diameter} ≈ 0.57, the coupling coefficient and power transfer can be optimal.
- Presence of outer Al ring affects the power transfer capability
- Greater the distance of outer ring to ferrite, better the coupling and power transfer capability



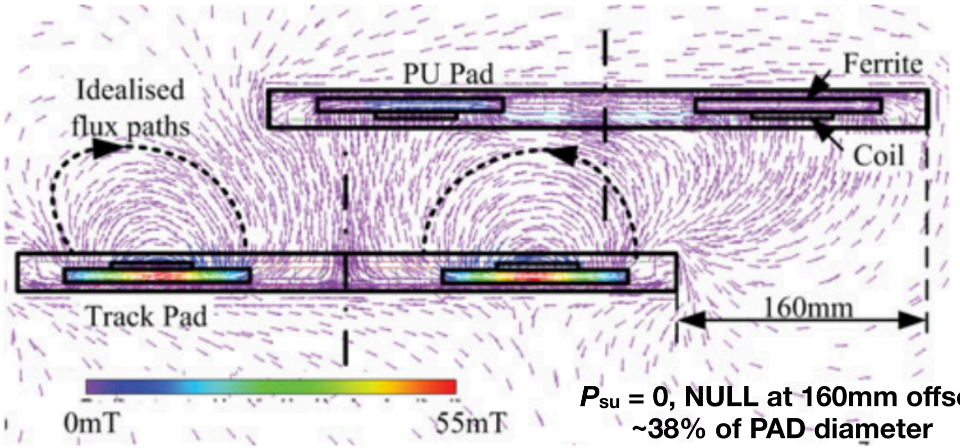


M. Budhia, G. A. Covic, and J. T. Boys, “Design and Optimization of Circular Magnetic Structures for Lumped Inductive Power Transfer Systems,” *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3096-3108, Nov. 2011.

Empirical Data (Univ. of Auckland)

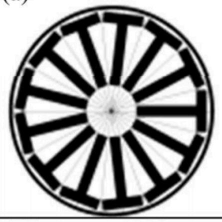
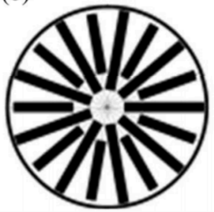


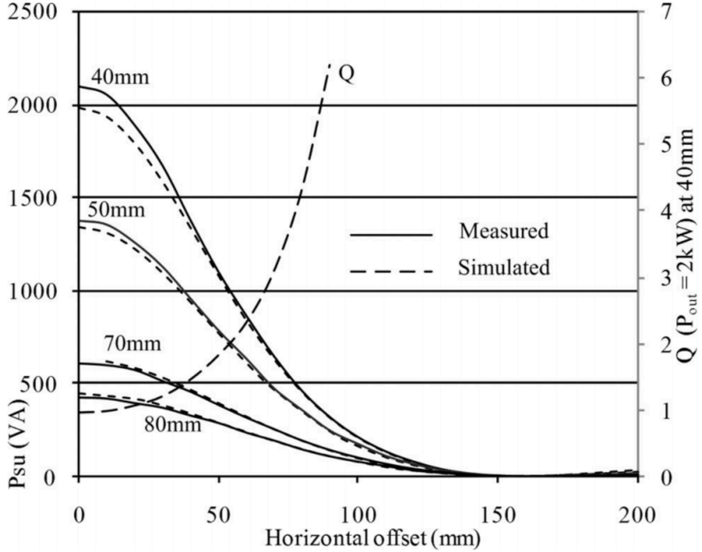
Flux density well below saturation which is around 200 mT for ferrite.



P_{su} = 0, NULL at 160mm offset
~38% of PAD diameter

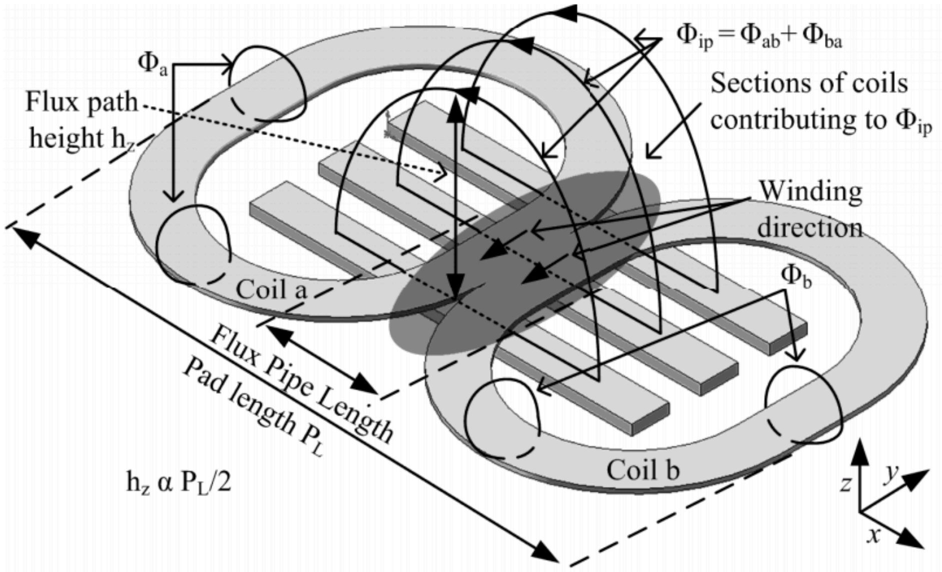
Flux extends to 1/4 of diameter for circular PAD, and to 1/2 of the length for rectangular PAD.

Pad Topology	(a) 	(b) 	(c) 	(d) 	(e) 
P_{su} at given Separation (VA)	100mm 3841 150mm 1236 200mm 435	100mm 3832 150mm 1212 200mm 420	100mm 3479 150mm 1102 200mm 383	100mm 2825 150mm 868 200mm 293	100mm 2480 150mm 775 200mm 264
No. of bars	32.5	31.5	33	21	18
Use (VA/cm^3)	3.34	3.44	2.98	3.80	3.89

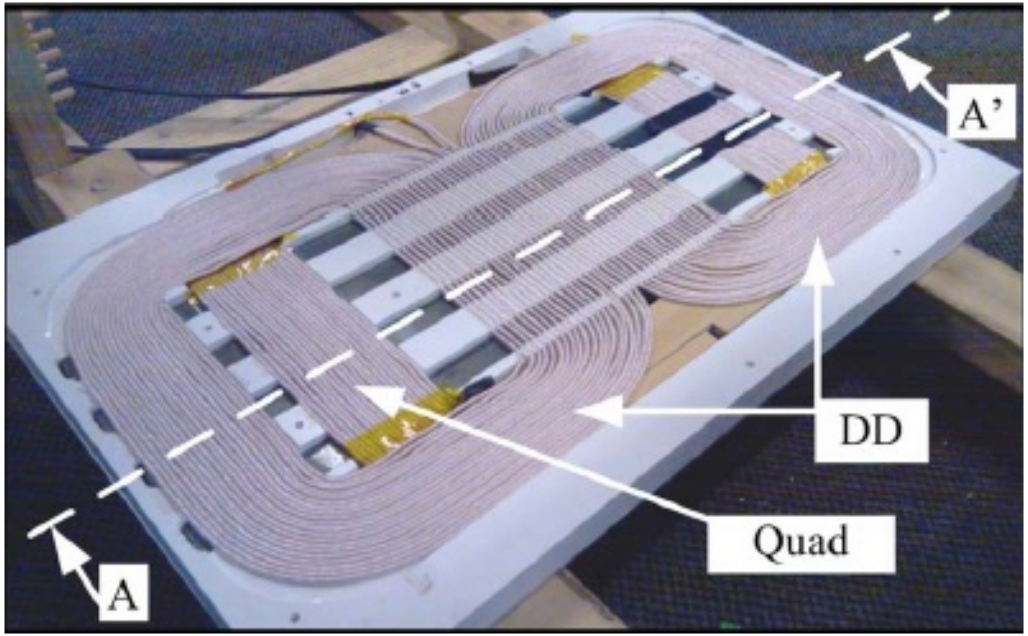


M. Budhia, G. A. Covic, and J. T. Boys, "Design and Optimization of Circular Magnetic Structures for Lumped Inductive Power Transfer Systems," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3096-3108, Nov. 2011.

DD-DDQ



DD at primary

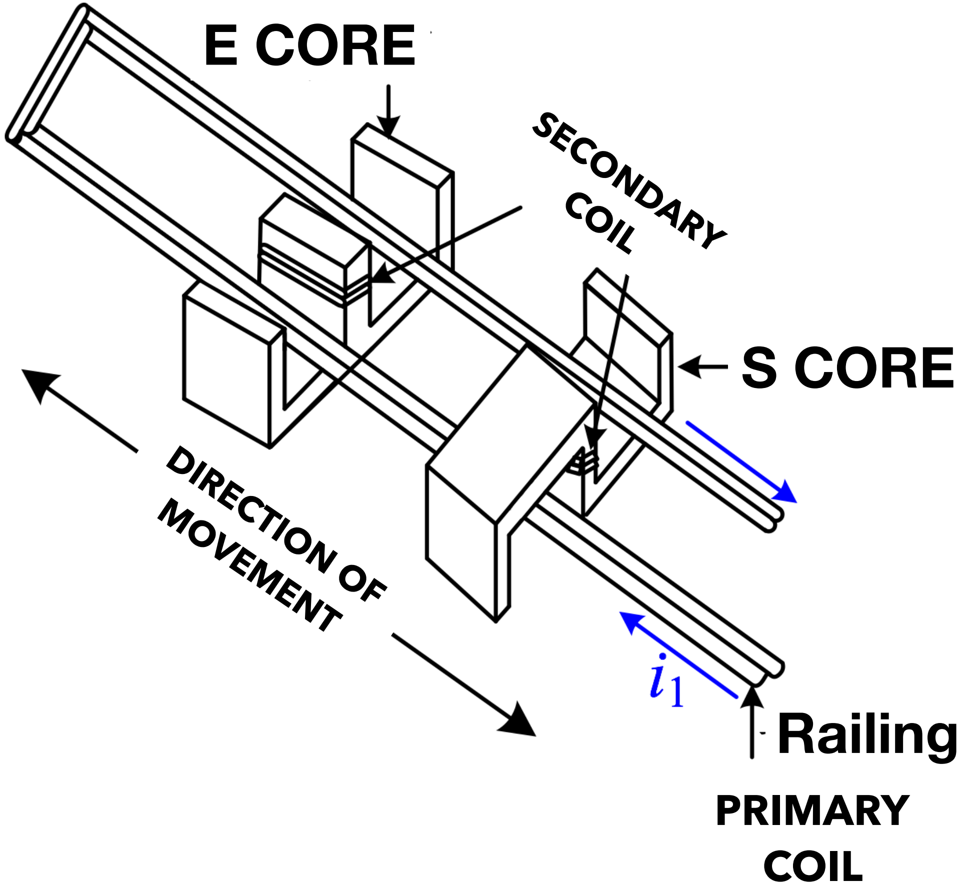


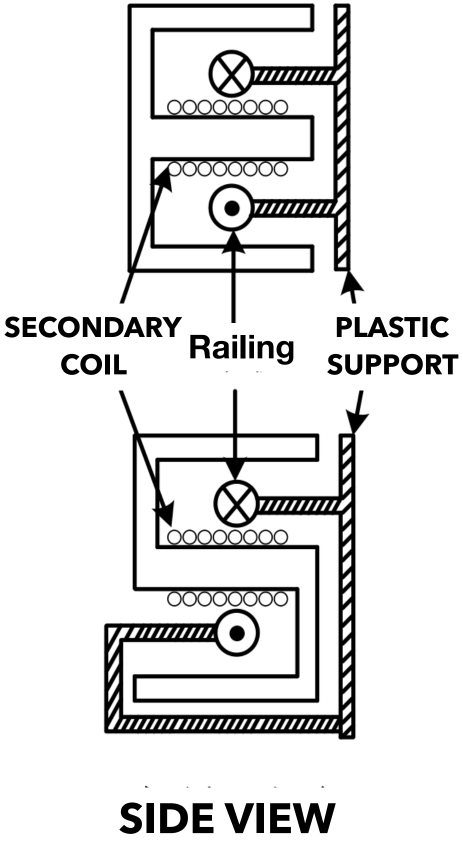
DD+Q at secondary

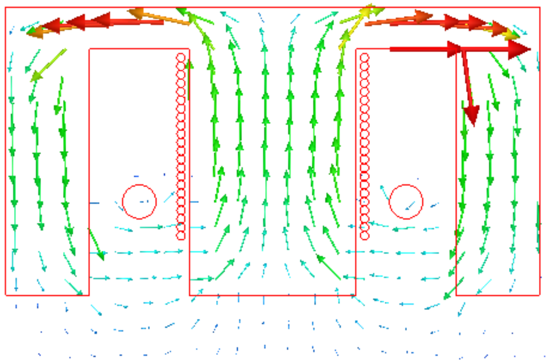
Basically the quadrature coil captures the flux at the null of the DD pad

M. Budhia, J. T. Boys, G. A. Covic, and C-Y. Huang, "Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 318–328, Jan. 2013.

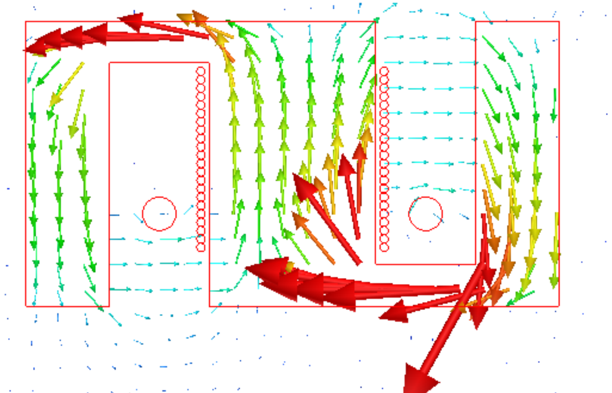
Wireless Power Transfer in Trams





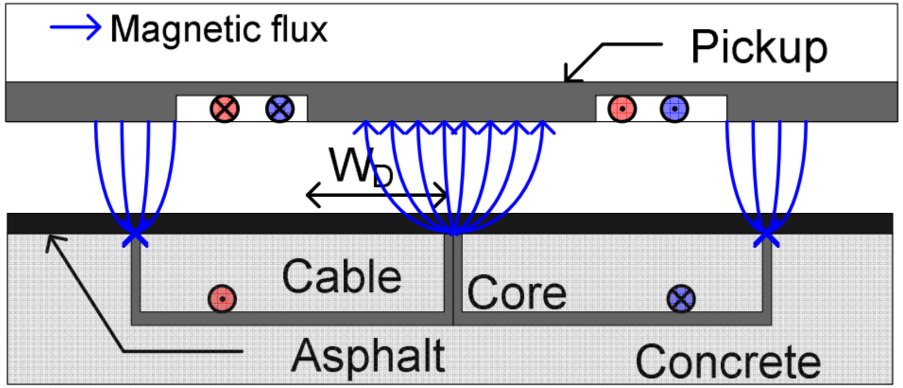


Fluxes partially cancel and less power transfer capability

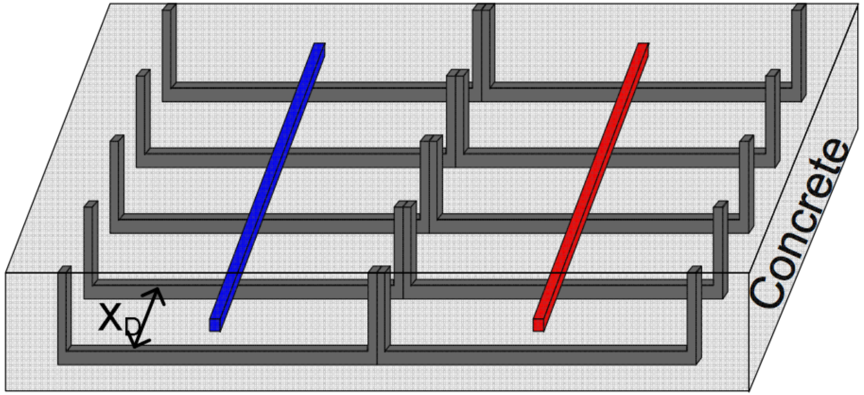


Less flux cancelled at the two sides and more power transfer capability

KAIST Bone Structure Core



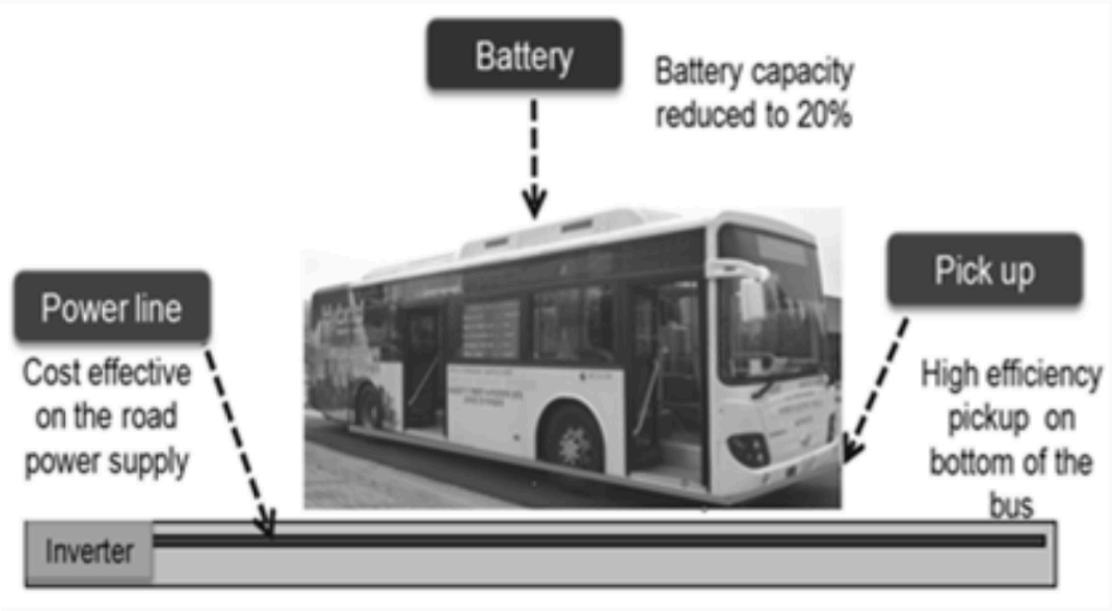
(a)



(b)

Amount of core significantly reduced.

Reduce EMF at center of road to below 60 mG to alleviate safety concern.



S. Lee, J. Huh, C. Park, N-S. Choi, G-H. Cho and C-T. Rim, “On-line electric vehicle using inductive power transfer system,” in Proc. IEEE ECCE, Sep. 2010, pp. 1598–1601.

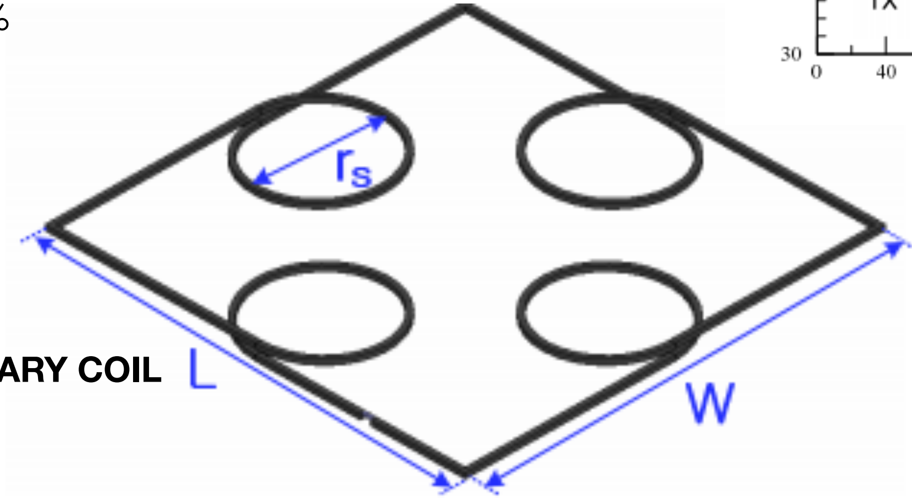
Coil Arrangement Enhancement

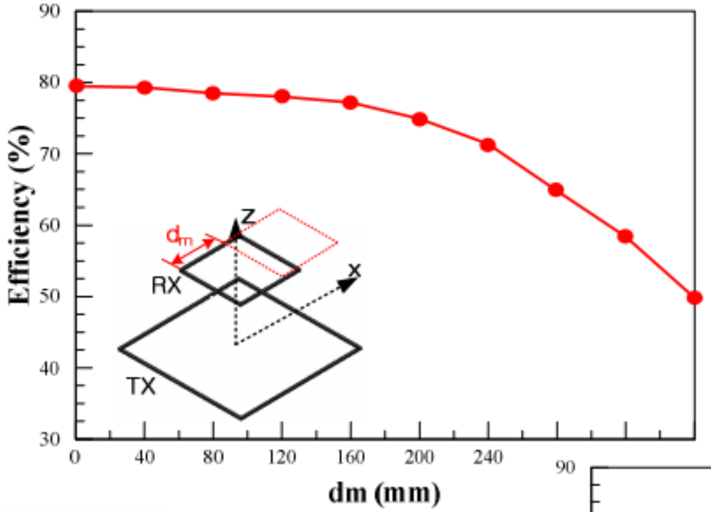
Small circular loops added on primary side.

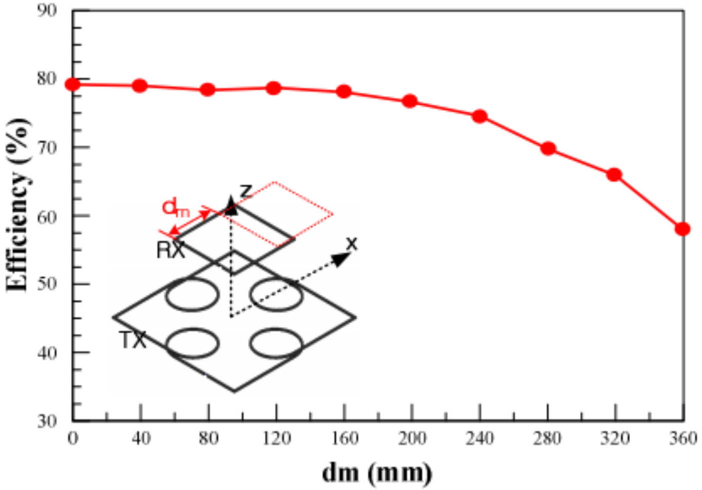
Experiment:

Primary coil 800 mm x 800 mm; secondary coil 400mm x 400mm; gap 30 mm; misalignment 0–360 mm; small loops 200 mm diameter

Efficiency improved from 79,5%–47,8% to 79%–57.9%





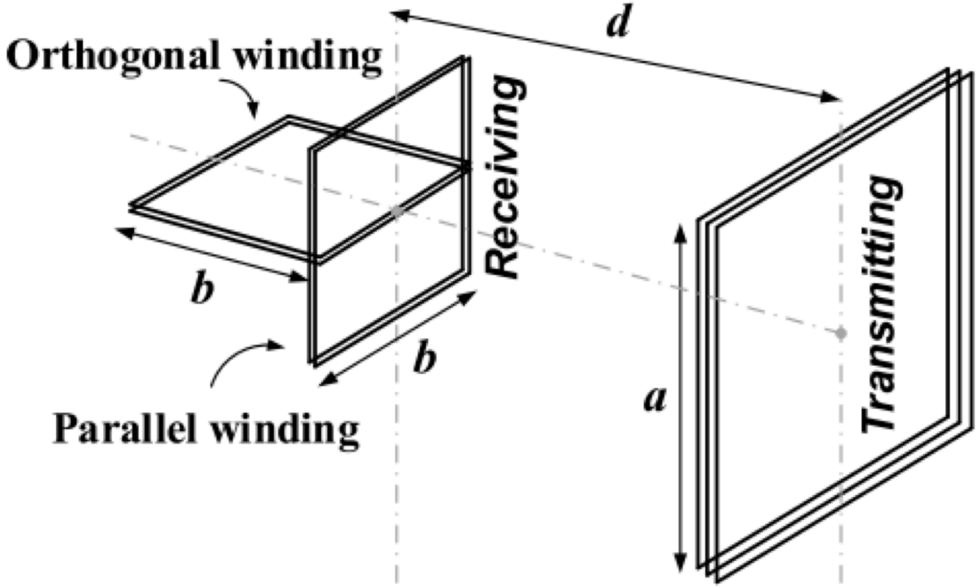


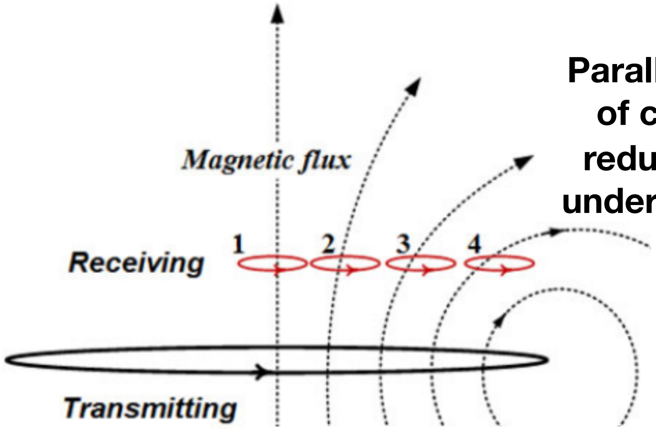
C-H. Ahn, K. Y. Kim, Y-H. Ryu, “A novel resonator for robust lateral-misalignment of magnetic resonance wireless power link,” IEEE International Symposium on Antennas and Propagation (APSURSI), 2013. pp. 844–845.

Reshaping Magnetic Fields

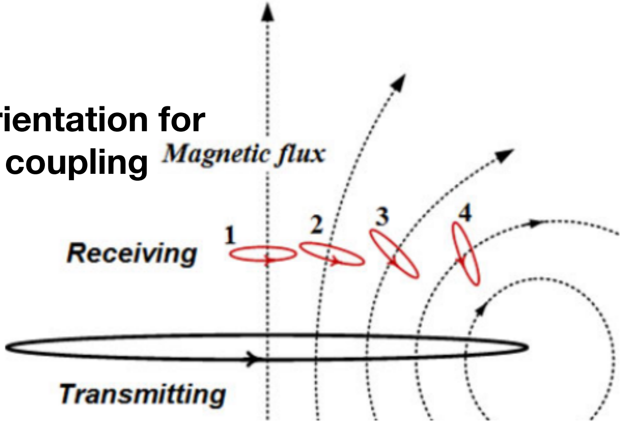
Two orthogonal coils in secondary

The pickup can be done in two directions, each working for one orientation and hence improving coupling under angular misalignment.





Parallel Orientation of coils leads to reduced coupling under misalignment

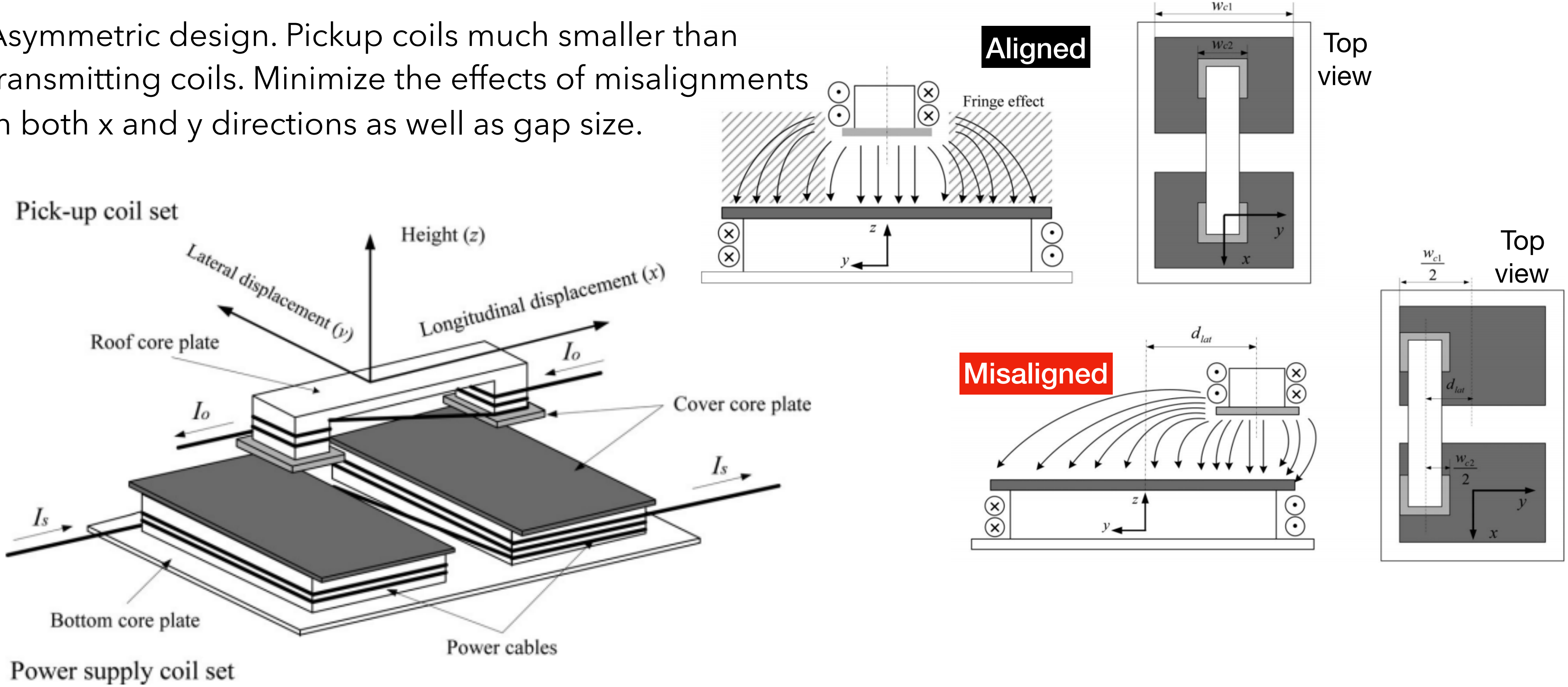


Ideal Orientation for max coupling

J. P. W. Chow, N. Chen, H. Chung, L. L. H. Chan, "An Investigation Into the Use of Orthogonal Winding in Loosely Coupled Link for Improving Power Transfer Efficiency Under Coil Misalignment," IEEE Trans. Power Electron., vol. 30, no. 10, pp. 5632–5649, Oct. 2015.

Asymmetric Design

Asymmetric design. Pickup coils much smaller than transmitting coils. Minimize the effects of misalignments in both x and y directions as well as gap size.



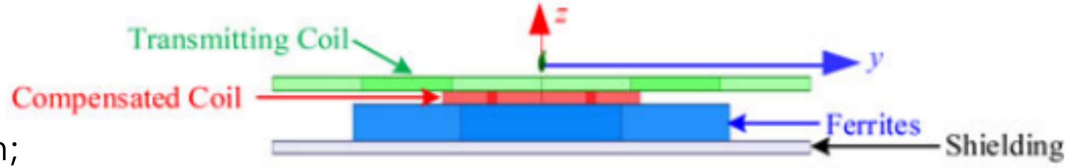
S. Y. Choi, J. Huh, W. Y. Lee, and C. T. Rim, "Asymmetric Coil Sets for Wireless Stationary EV Chargers With Large Lateral Tolerance by Dominant Field Analysis," IEEE Trans. Power Electron., vol. 29, no. 12, pp. 6406–6420, Dec. 2014.

Compensation Coil Integrated Magnetics

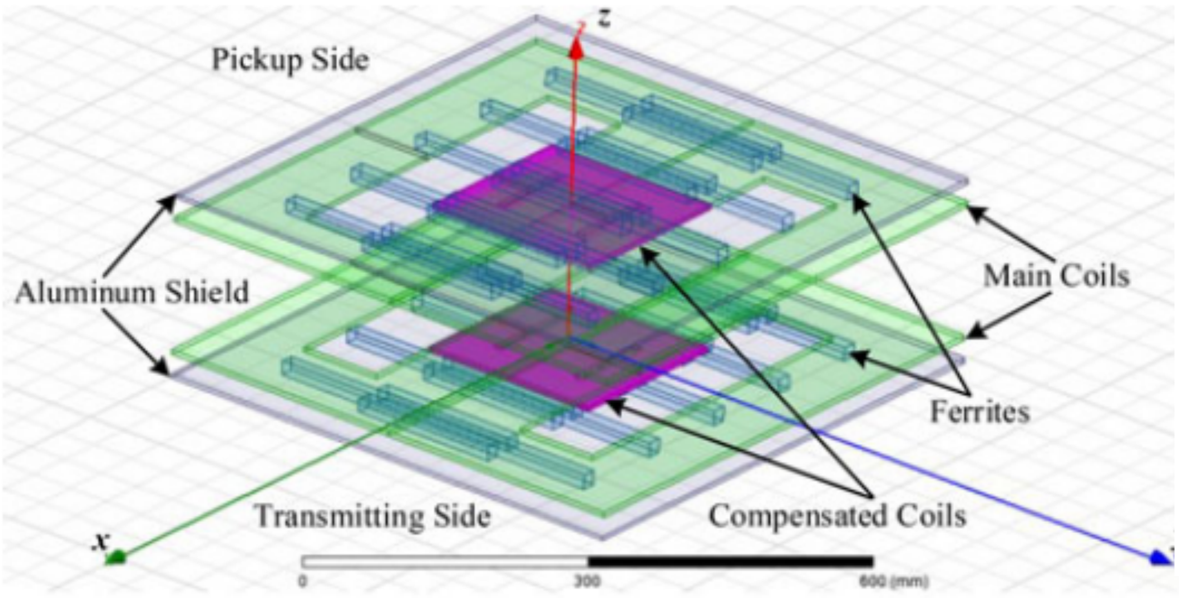
LCC compensation with compensation coils wound on the same core as the DD pad.

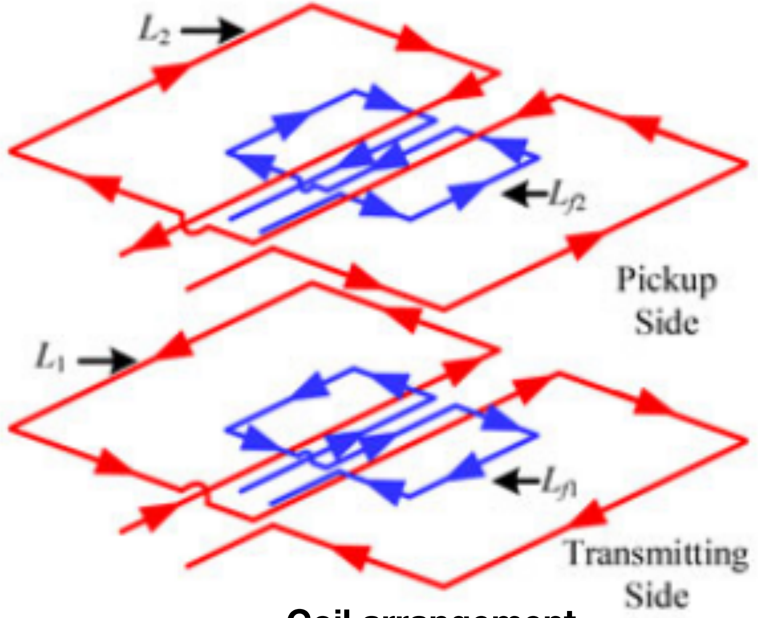
Size 600 mm x 600 mm; compensation coil 200 mm x 200 mm;

Gap 150 mm; frequency 95 kHz; max efficiency 95.36%



Cross-sectional view





Coil arrangement

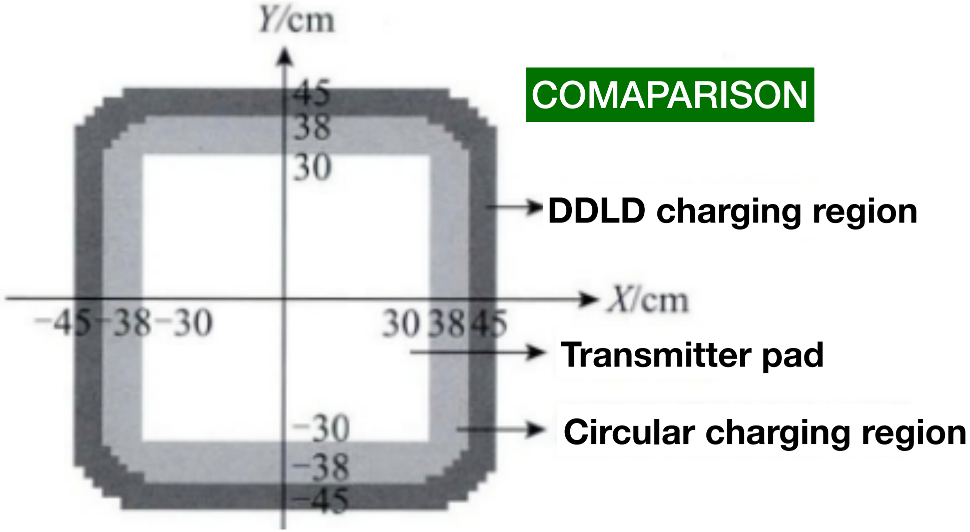
J. Deng, W. Li, T. D. Nguyen, S. Li, and C. Mi, "Compact and Efficient Bipolar Coupler for Wireless Power Chargers: Design and Analysis," IEEE Trans. Power Electron., vol. 30, no. 11, pp. 6130–6140, Nov. 2015.

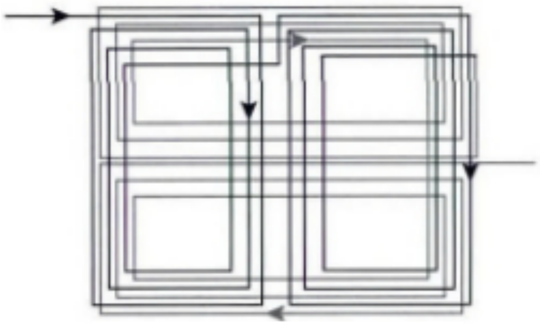
DDLD Charging Pad

Chongqing University

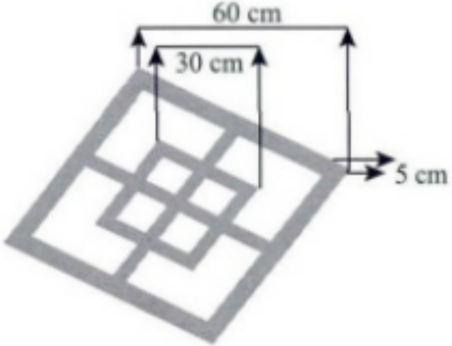
DDLD design for magnetic coupling.

Wider alignment tolerance and wider charging gap.

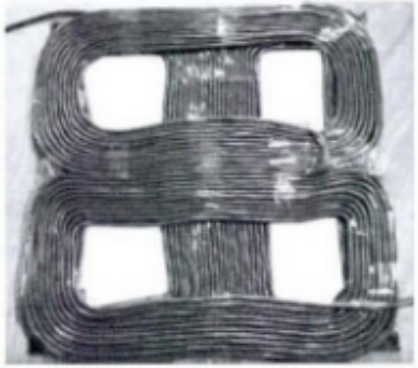




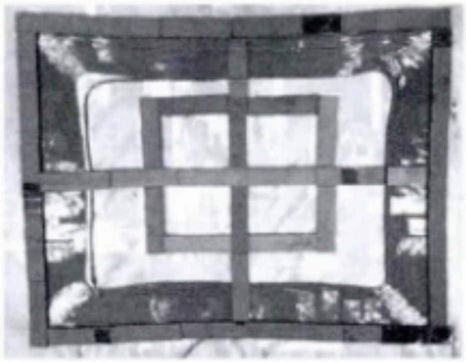
Winding arrangement



Ferrite design



Transmitter coil



Receiver coil

王智慧，胡超，孫躍，戴欣，“基於輸出能效特性的IPT系統磁耦合機構設計“，電子技術學報，第30卷，第19期，26-31頁，2015.

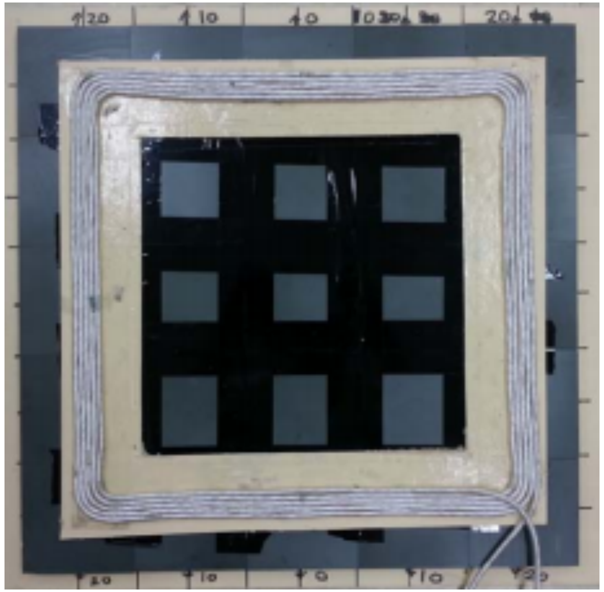
Add-on Coils

KAIST: Additional diagonal coils in primary side

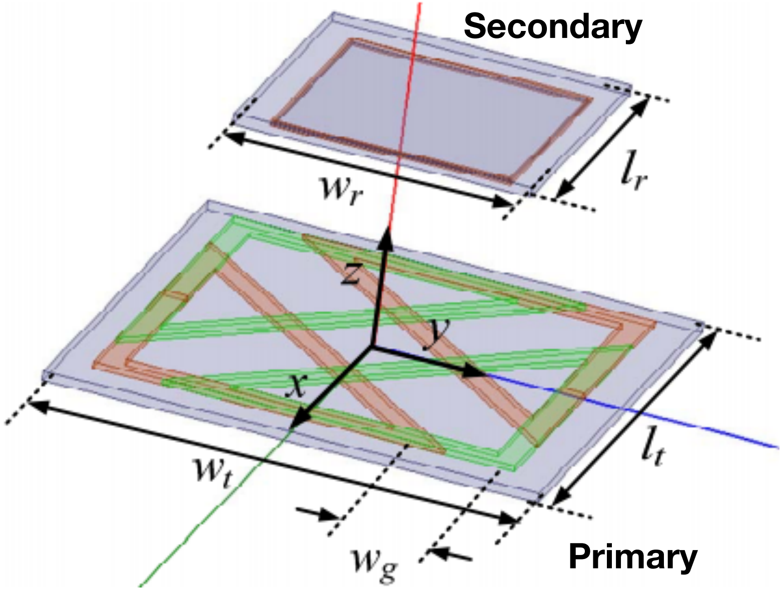
Added coils wounded through diagonal lines

Improve misalignment along the diagonal directions

Traditional coils

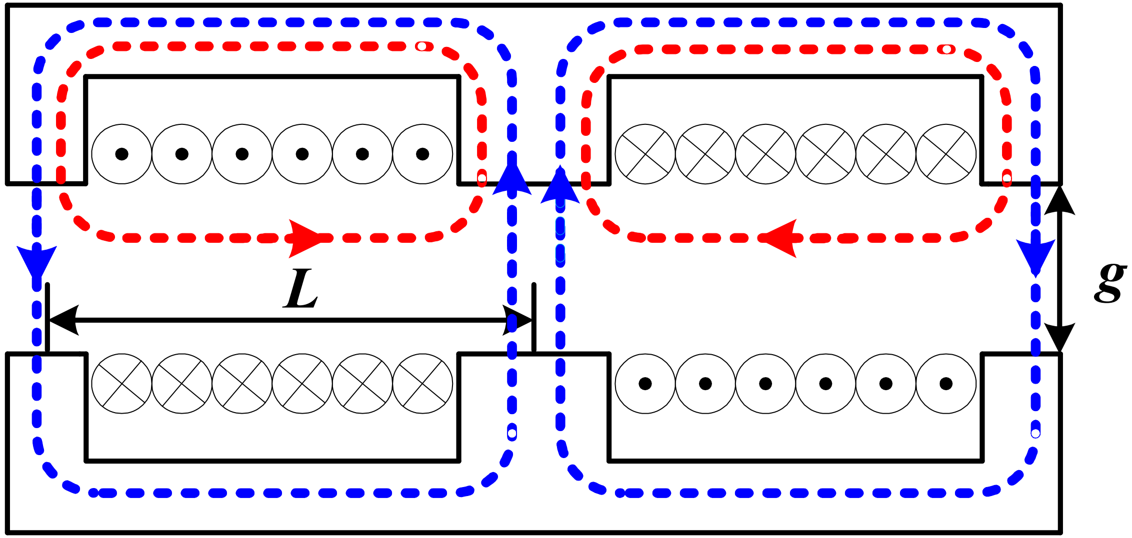


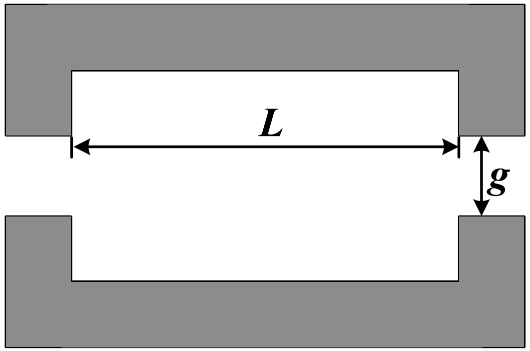
DQ cross coils



S. Y. Jeong, S. Y. Choi, M. R. Sonapreetha, and C. T. Rim, "DQ-quadrature power supply coil sets with large tolerances for wireless stationary EV chargers," IEEE PELS Workshop on Emerging Technologies: Wireless Power (WoW), 2015.

Contactless Transformer Analysis



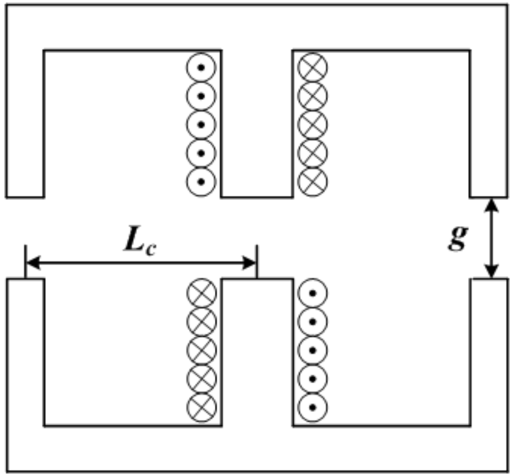


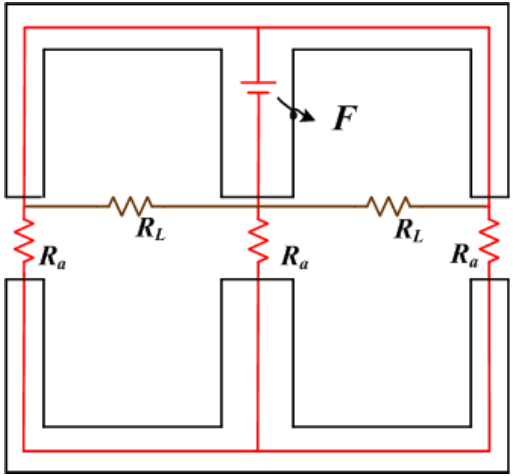
Coupling coefficient *k* depends on the ratio *L*/*g*.

Larger *L* gives larger *k*.

Smaller *g* gives larger *k*.

Nishimura Formula (Conventional reluctance model)

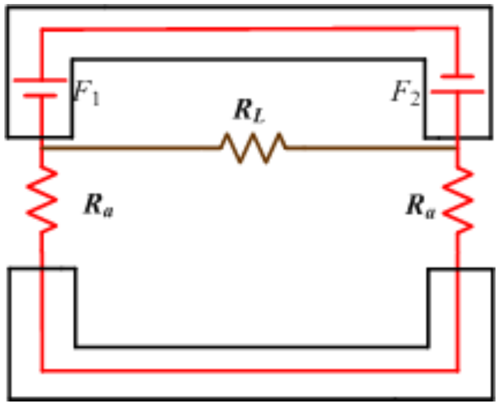


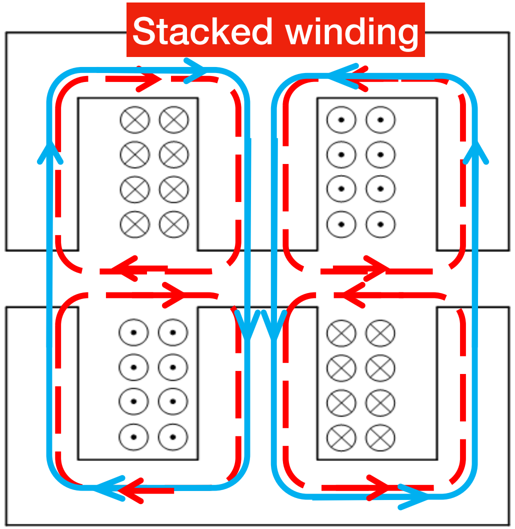


$$F = F_1 + F_2$$

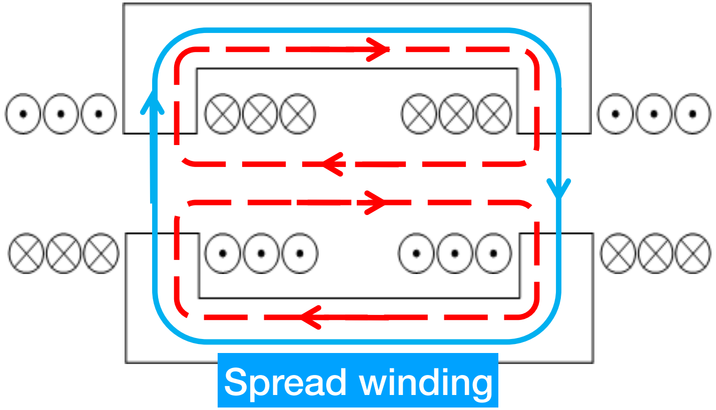
$$k = \frac{(F_1 + F_2)/2R_a}{(F_1 + F_2)/2R_a + (F_1 + F_2)/R_L} = \frac{1}{(2g / L_c) + 1}$$

Thus, k is affected by the core and the winding arrangement.

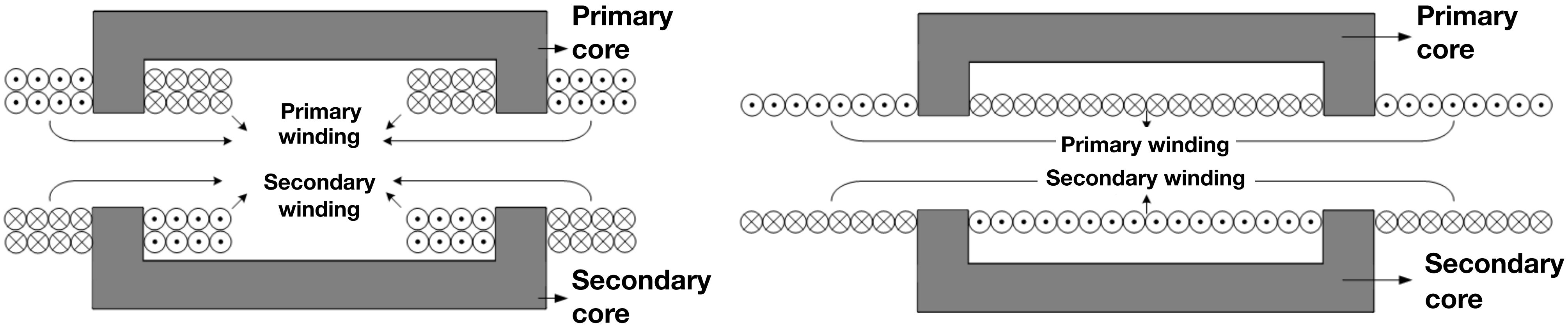




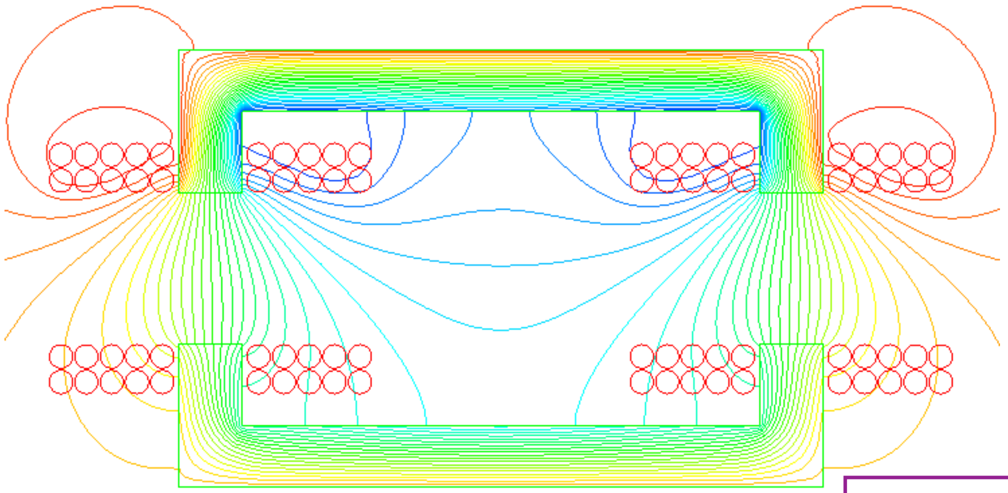
Changing the shape of the core, widening L



Winding: Stacked vs Spread



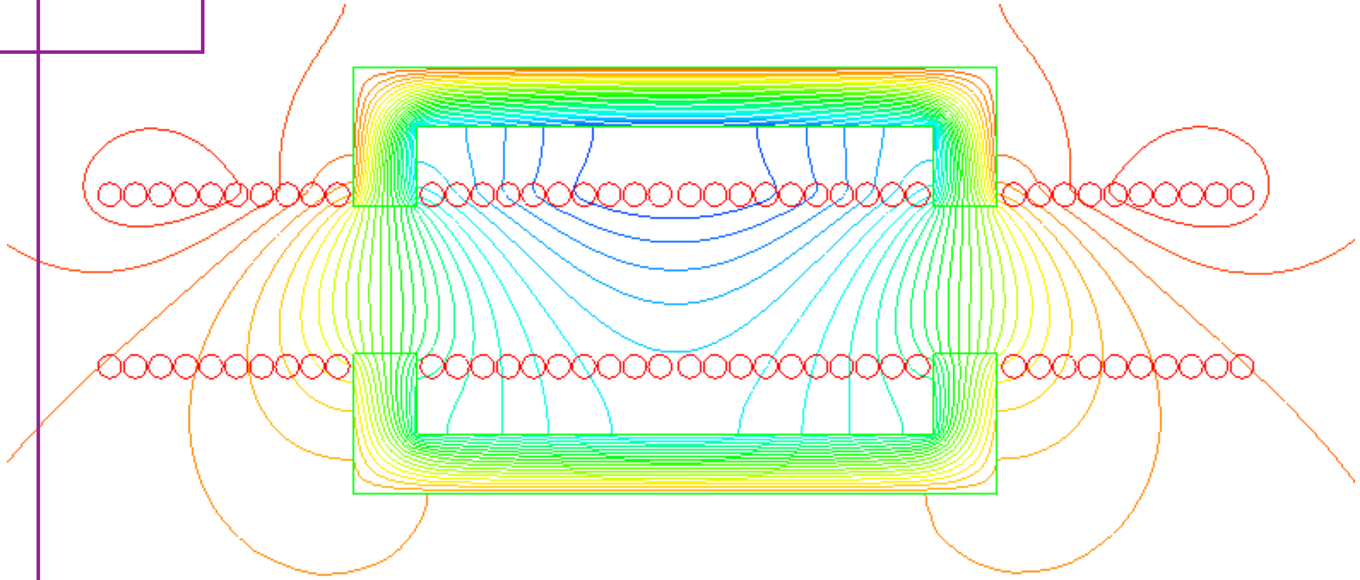
WINDING	CORE	Core Weight (gram)	L (mm)	Coupling Coeff.
Stacked	Planar U43 (Planar E with middle column removed)	59	34.7	0.39
Spread				0.46
Experimental Conditions：Both primary and secondary coils are 25 turns; gap; frequency 300 kHz				



STACKED WINDING

The stacked coil suffers the clouding effect reducing the flux linking through the gap. Some flux does not link to the secondary.

SPREAD WINDING has better coupling



Limitations

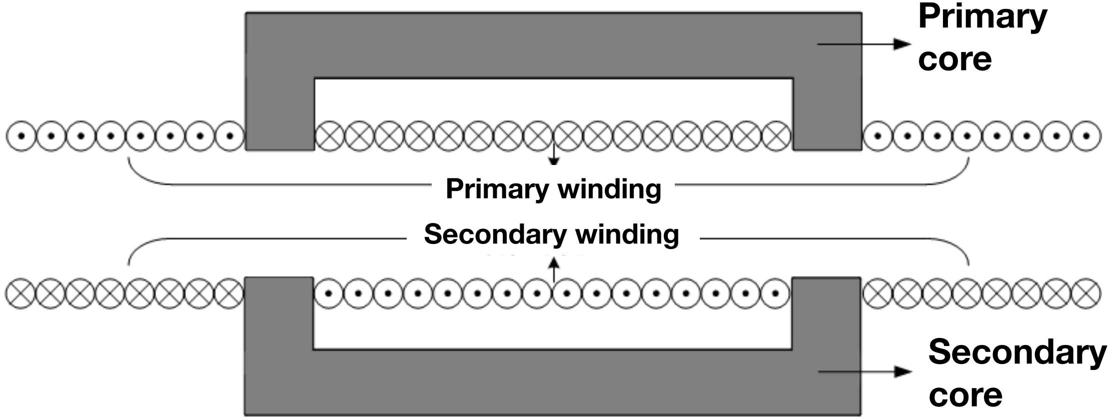
Nishimura formula cannot give consistent estimates of coupling coefficient for different experimental settings.

Experiment 1: Comparing planar core U43 with *L* = 34.7 mm with E64 core with *L* = 21.8 mm, same gap, the U43 has lower *k*!! Larger *L* gives smaller *k*!

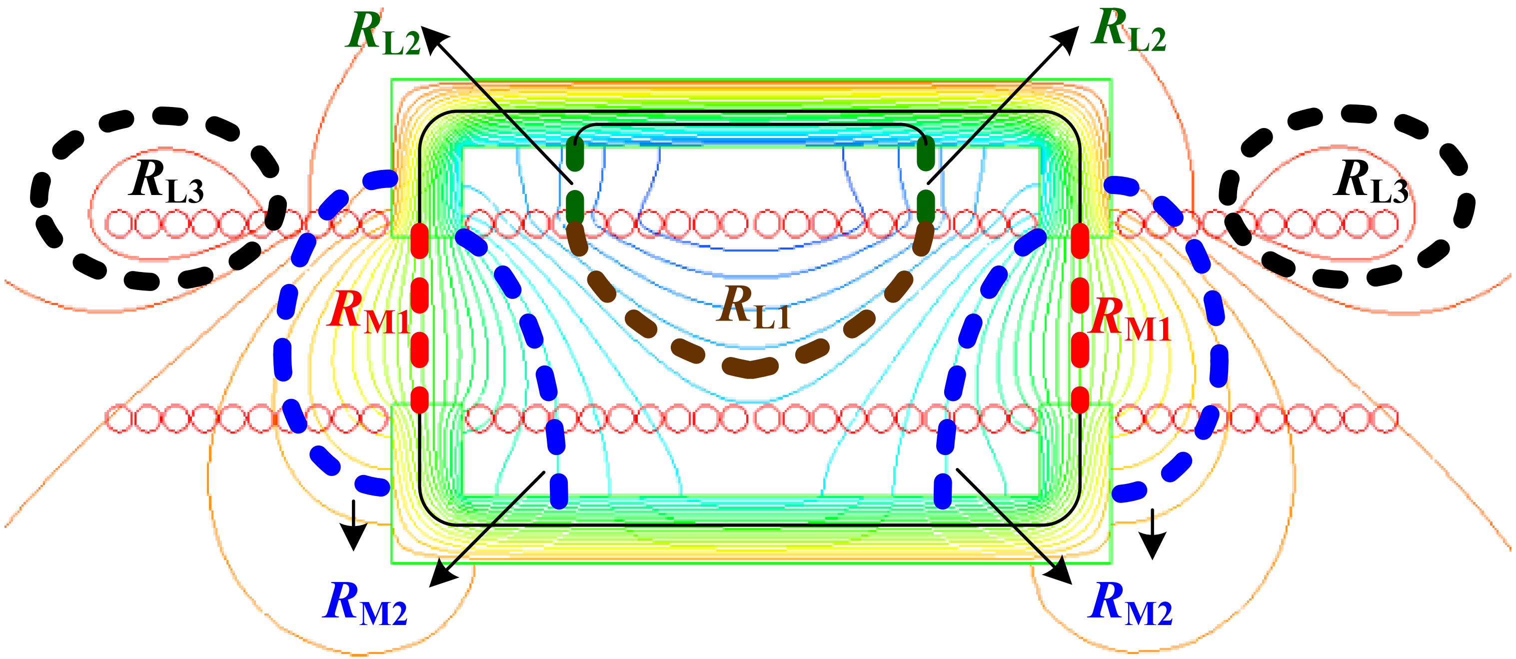
Experiment 2: Comparing U64 core (E64/10/50 without middle column) with *L* = 34.7 mm, with U43 core with L = 53.8 mm, gap at 10 mm, the coupling *k* changes only from 0.46 to 0.48. Not consistent with the formula. The increased *L* gives too little increase in *k!*

However, the formula gives k = 0.634 for U43, and k = 0.64 for U64, which are much bigger than experimentally measured values.

The Nishimura formular over-estimates *k*.



Optimization by magnetic path consideration

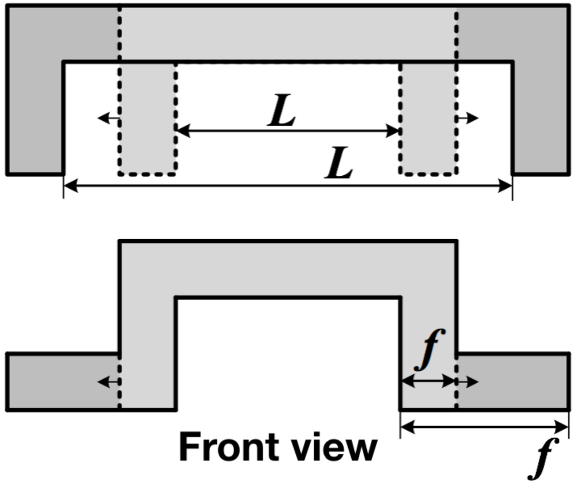


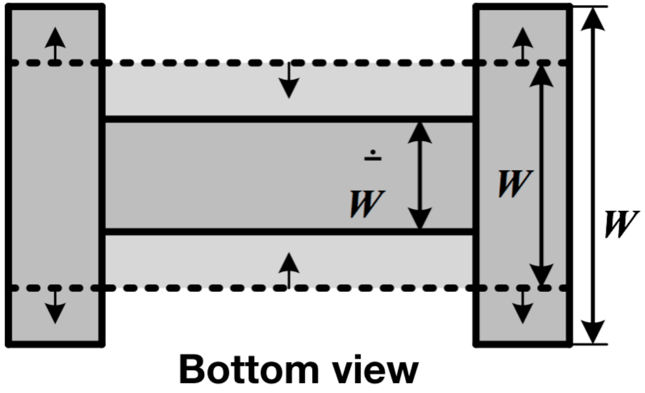
Reduce RM1 and RM2, increase RL1, RL2 and RL3.

Optimization/Enhancement Method

Increase *L* so as to reduce R_{M2}

Increase *f* so as to reduce R_{M1}

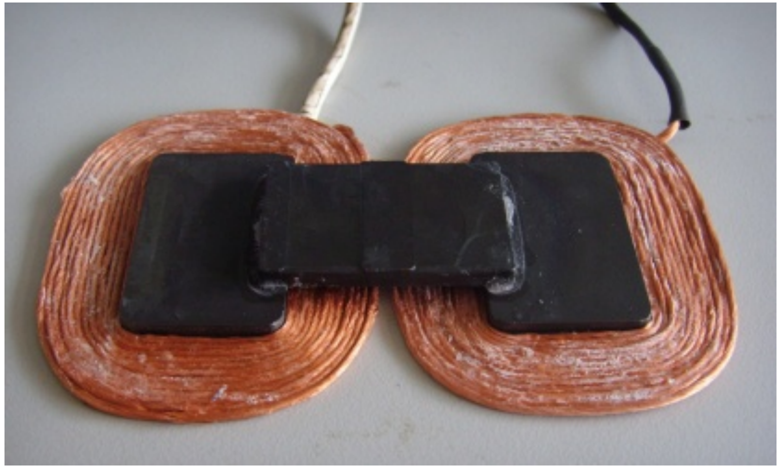




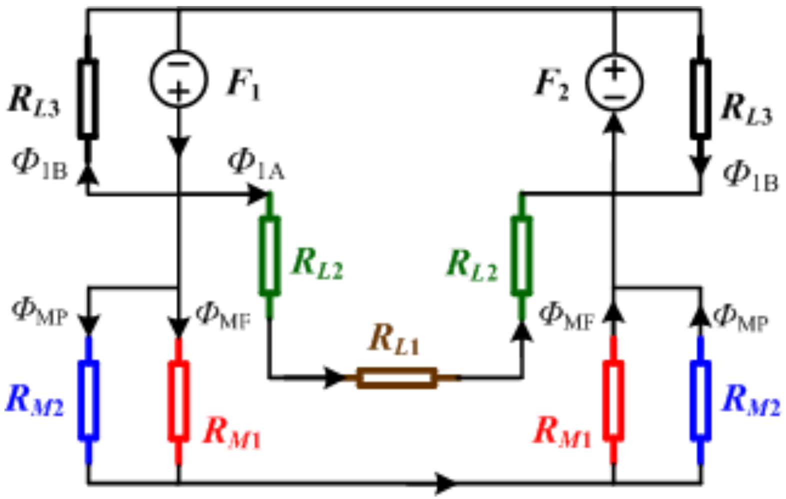
Increase *W* of side columns so as to reduce R_{M1} and R_{M2}

Reduce *W* of center column so as to increase R_{L1} and R_{L2}

Planar U core Extended rectangular coil



Modeling of Contactless Transformer



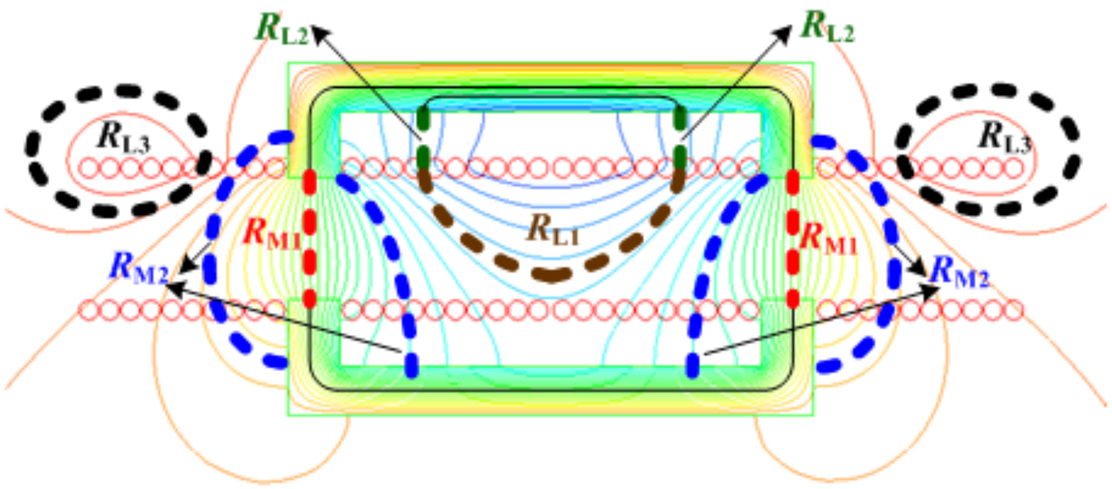
Magnetic path model

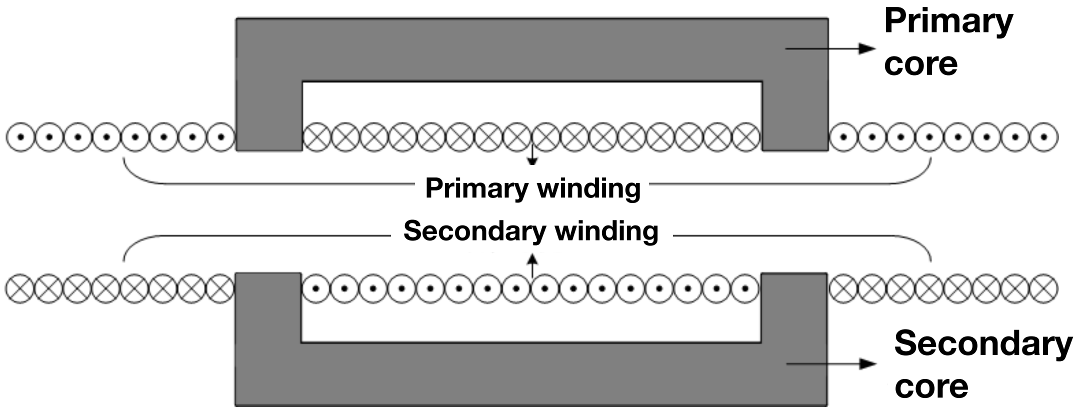
Leakage inductance path resistance: R_{L1}, R_{L2} and R_{L2}

Full coupled mutual inductance path resistance: R_{M1}

Partial coupled mutual inductance path resistance: R_{M2}

Full/partial coupling: Primary and secondary coils are linked fully/partially.

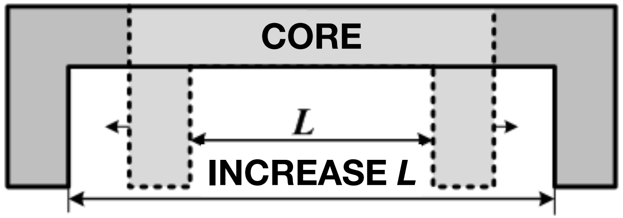




Enhancement of Core Structure

Traditional approach

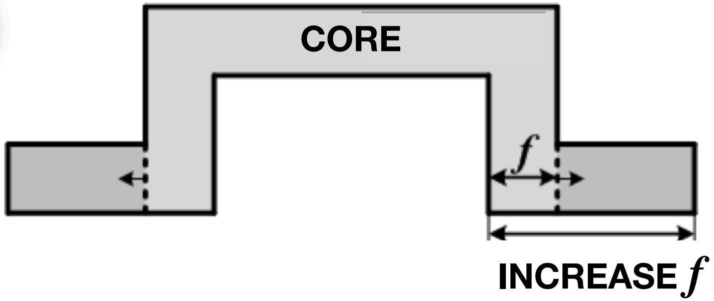
Increase coupled magnetic path; reduce leakage path

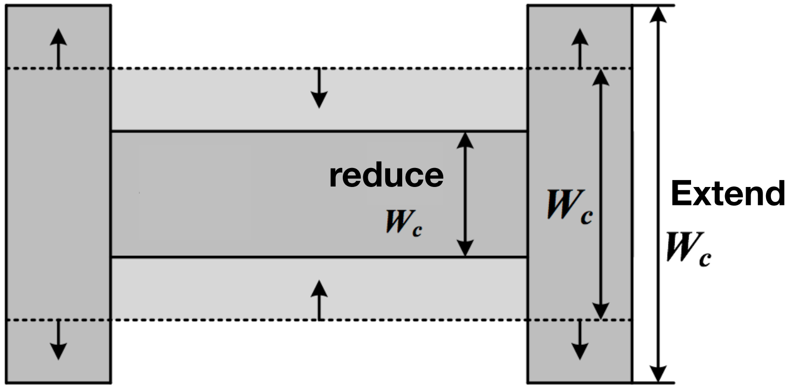


Enhancement from systematic analysis

Transformer core modification

L is about twice the gap size

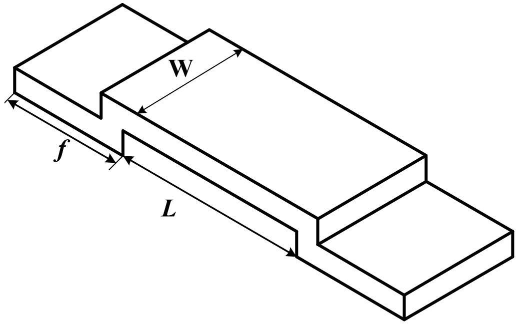




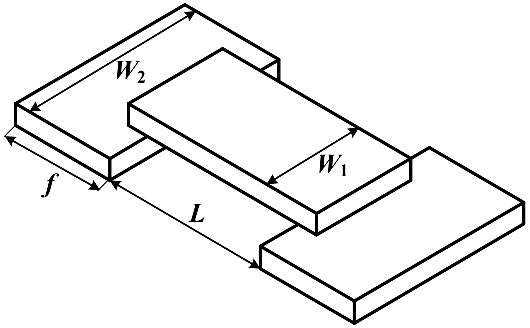
New core structure significantly enhances coupling

Extended Planar U-cores

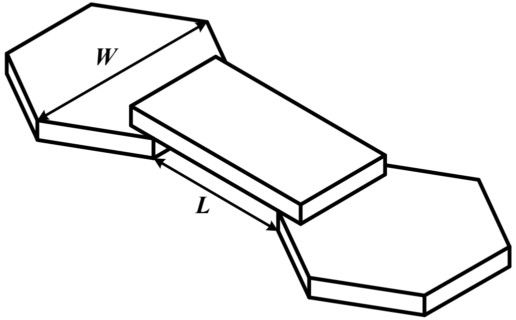
One-direction extension



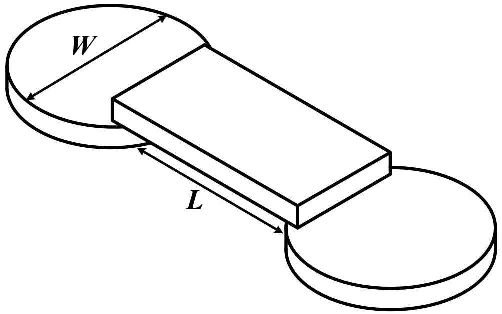
Two-direction extension



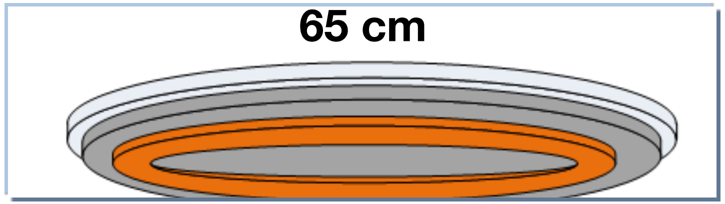
Polygon extension

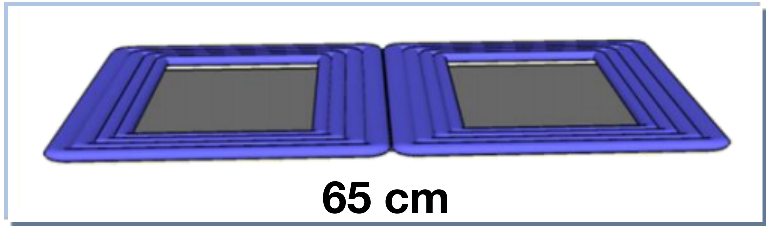


Circular extension



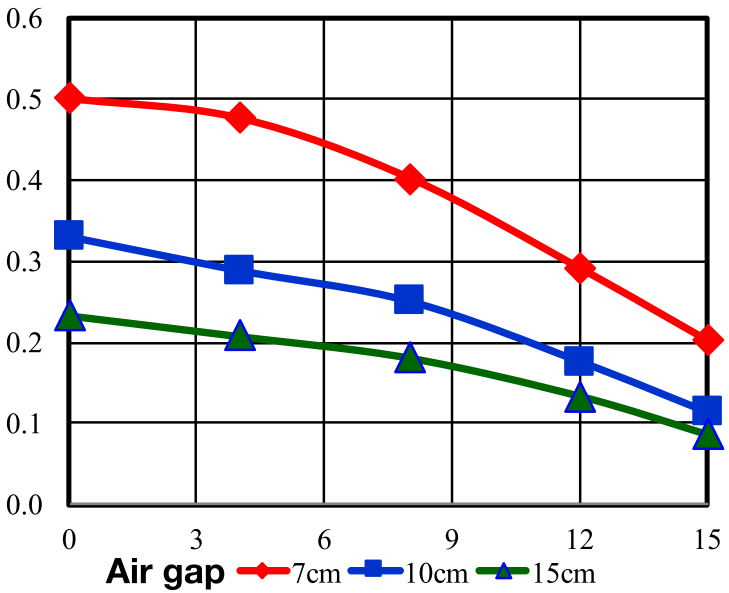
Misalignment





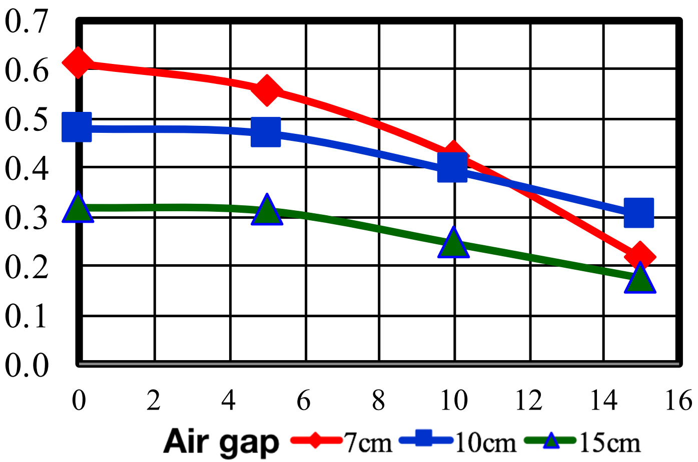
CIRCULAR PAD

coupling coeff vs. displacement



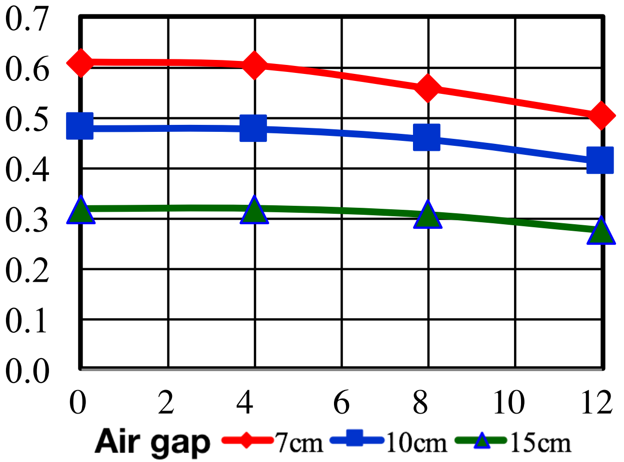
DD PAD

coupling coeff vs. x-displacement



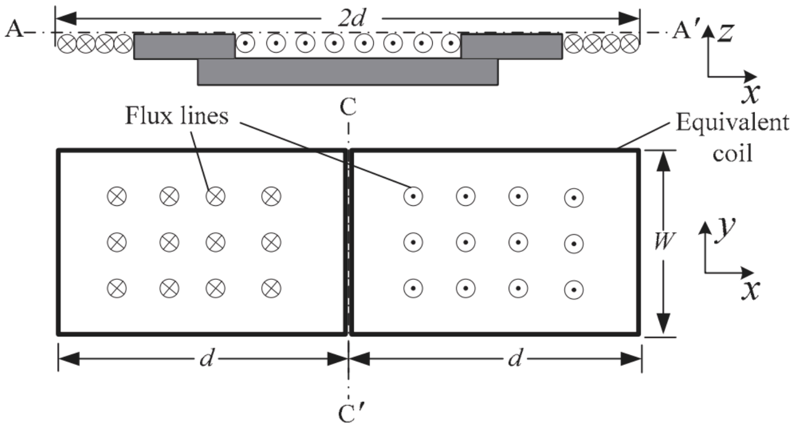
DD PAD

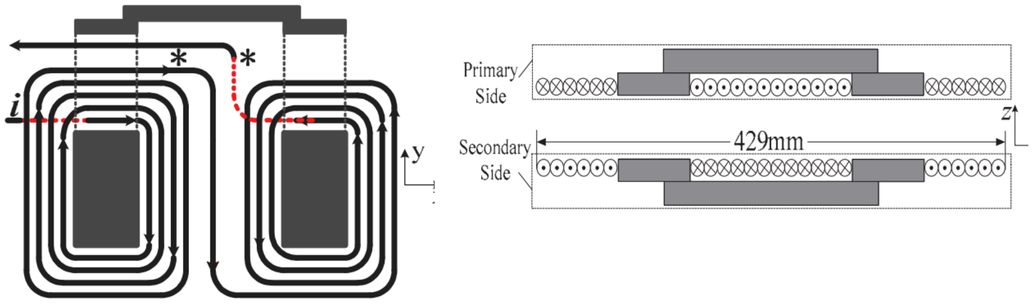
coupling coeff vs. y-displacement



Detailed Models of DD Pads

(Ke *et al.*, IEEE ECCE 2016)





(a) Coil structure (b) Length of the transformer

Key analysis:

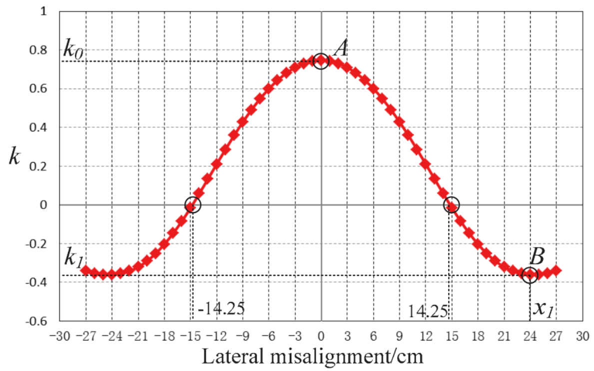
Calculation of coupling coefficient
Null position (offset at which coupling is zero)
Model for misalignment

$$k(x) = a\sin(bx + c)e^{mx} + h$$ by simulation

$$\Psi_x = BW(2d - 3x)$$

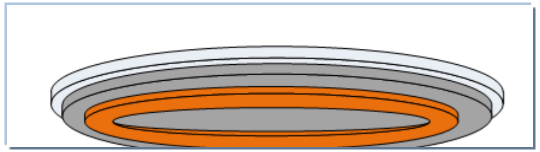
NULL position at

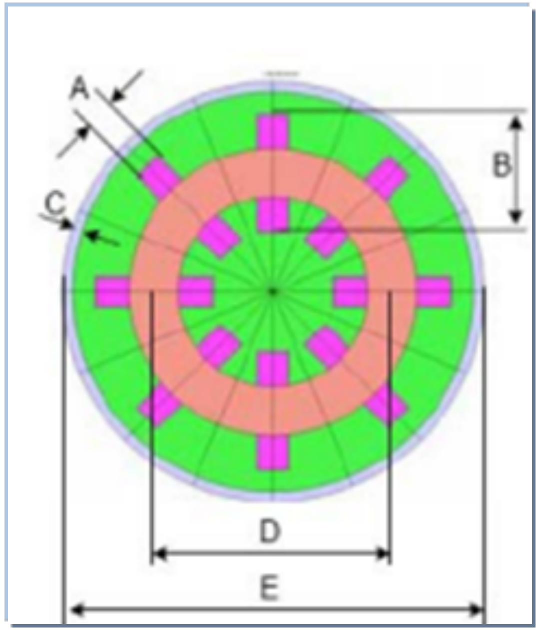
$$x = 2d/3$$



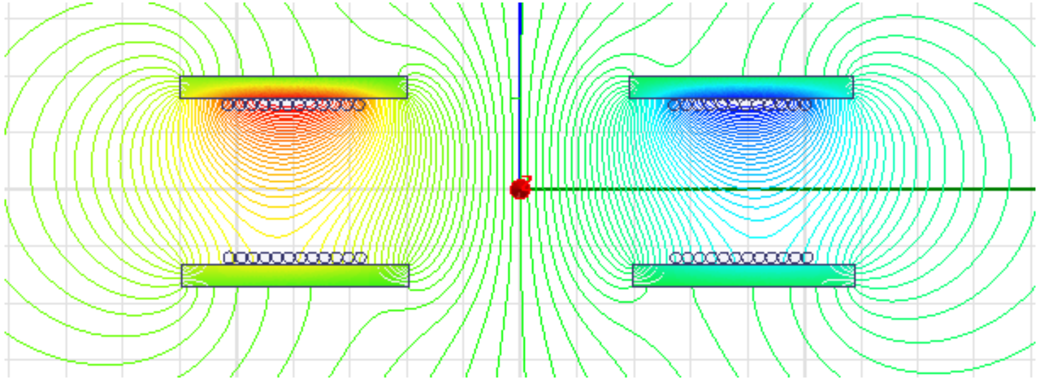
G. Ke, Q. Chen, L. Xu, S. C. Wong, and C. K. Tse, "A Model for coupling under coil misalignment for DD pads and circular pads of WPT systems," *IEEE Energy Conversion Congress and Exposition,* (IEEE ECCE 2016), Milwaukee, USA, September 2016.

Circular Pad

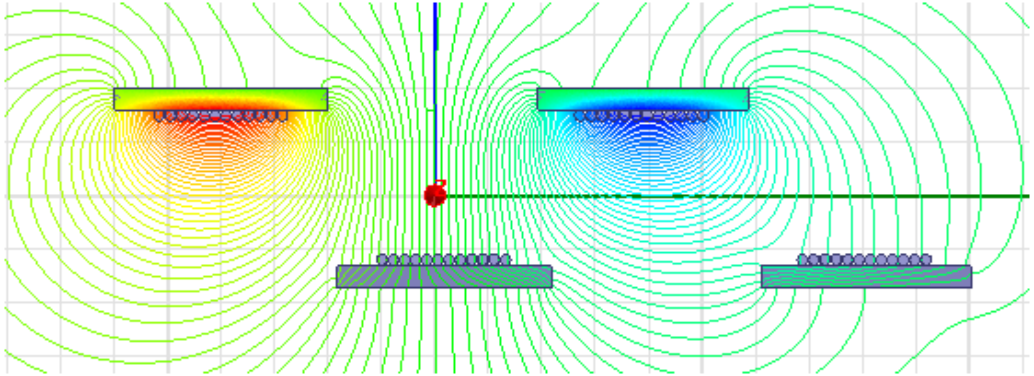




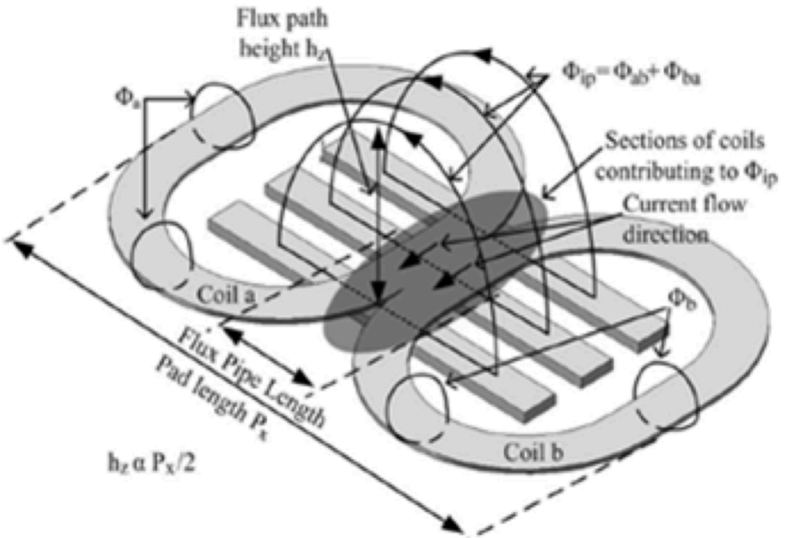
k = 0.515

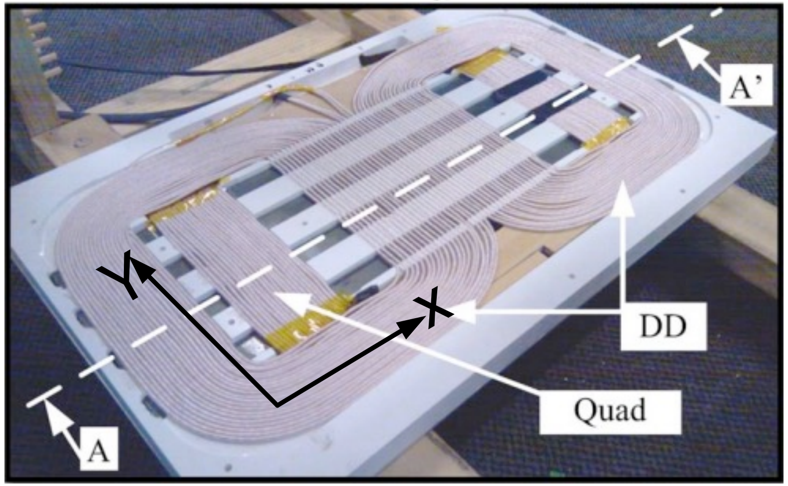


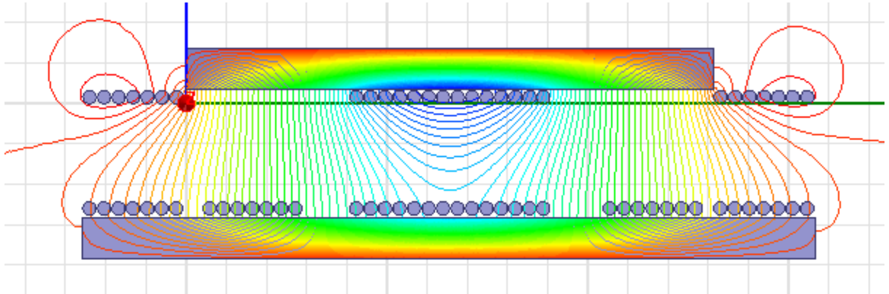
k = 0.135



DDQ Pad

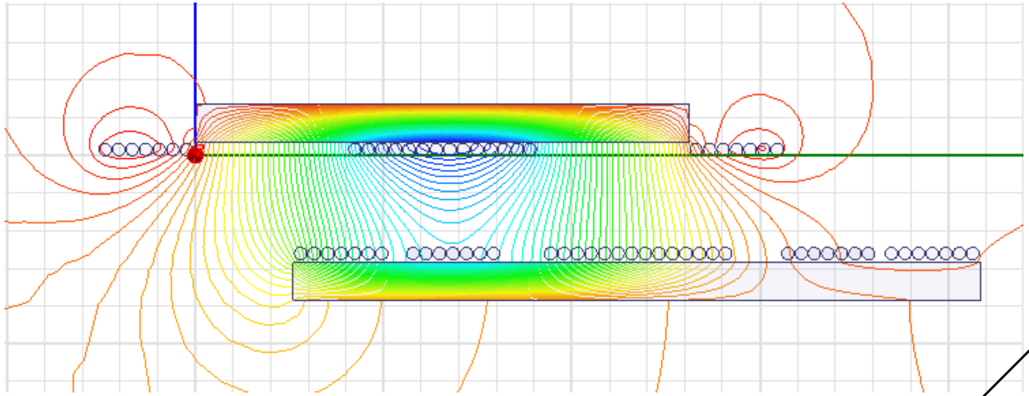






k = 0.723

k_Q = 0.143

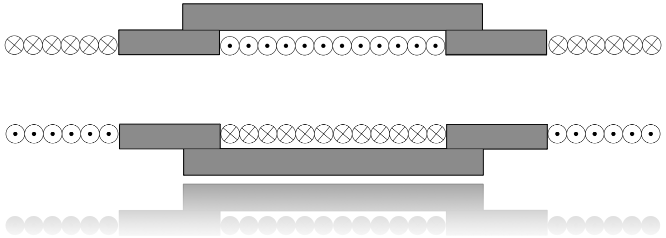


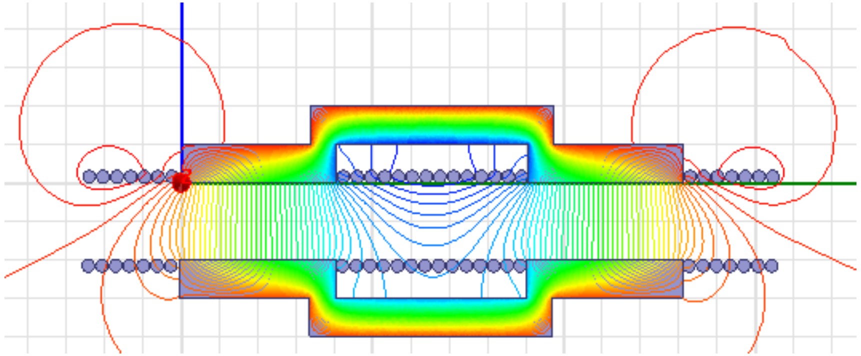
k = 0.081

k_Q = 0.623

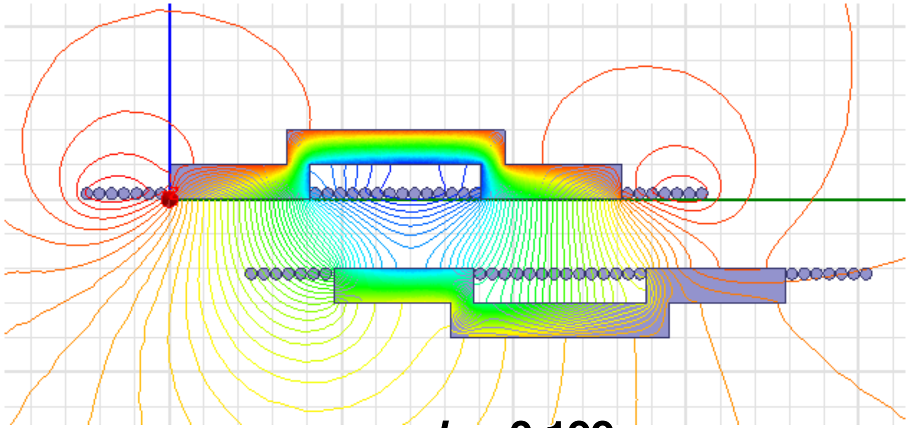
Quadrature coil links flux when misaligned

Extended U-core Transformer



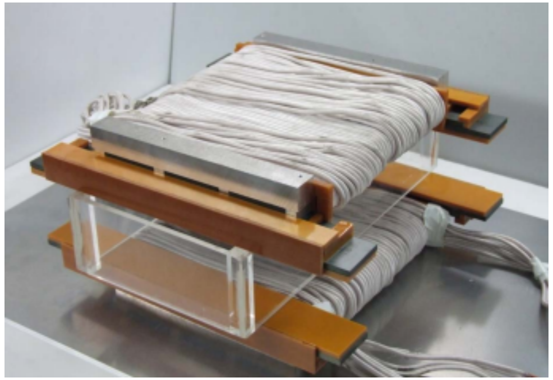


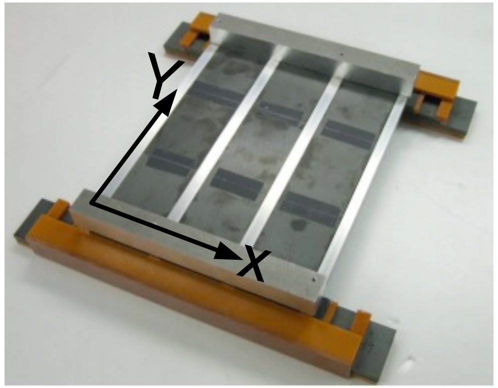
k = 0.763

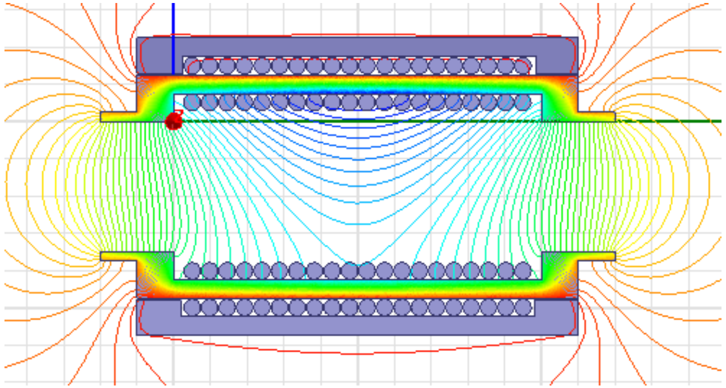


k = 0.199

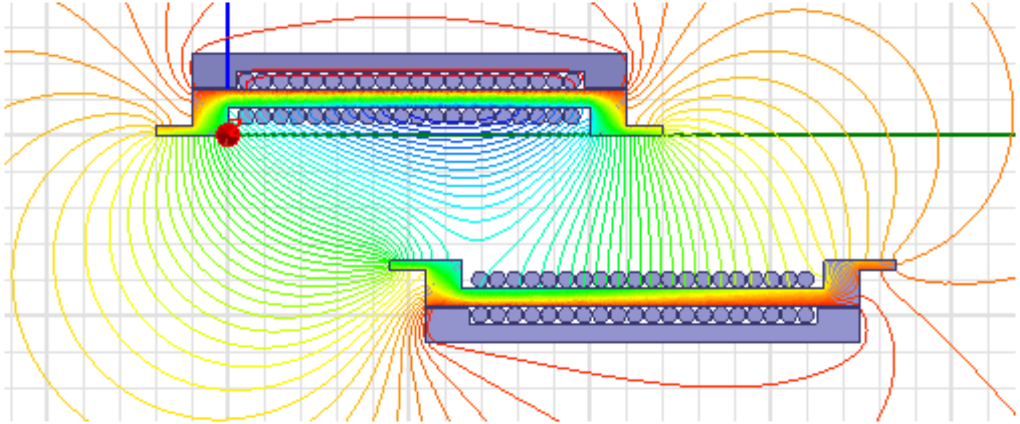
Double-sided Core Transformer





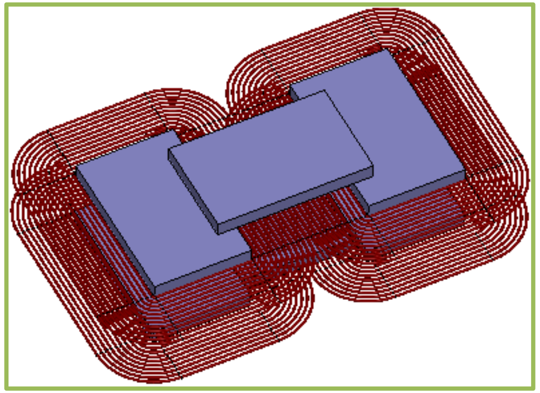


k = 0.402

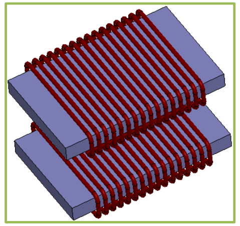


k = 0.179

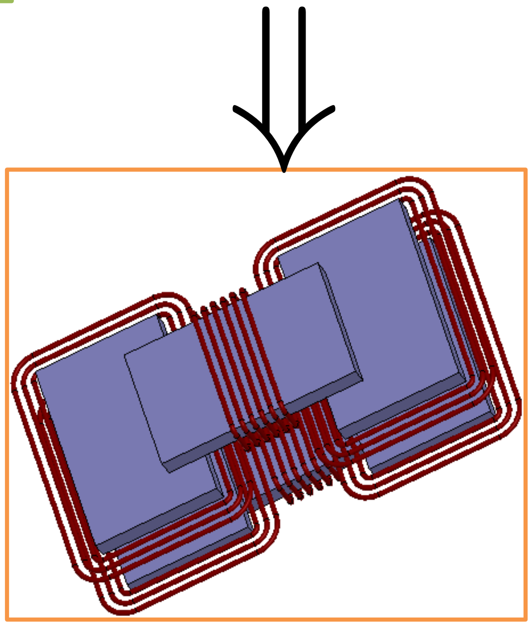
Additional Winding

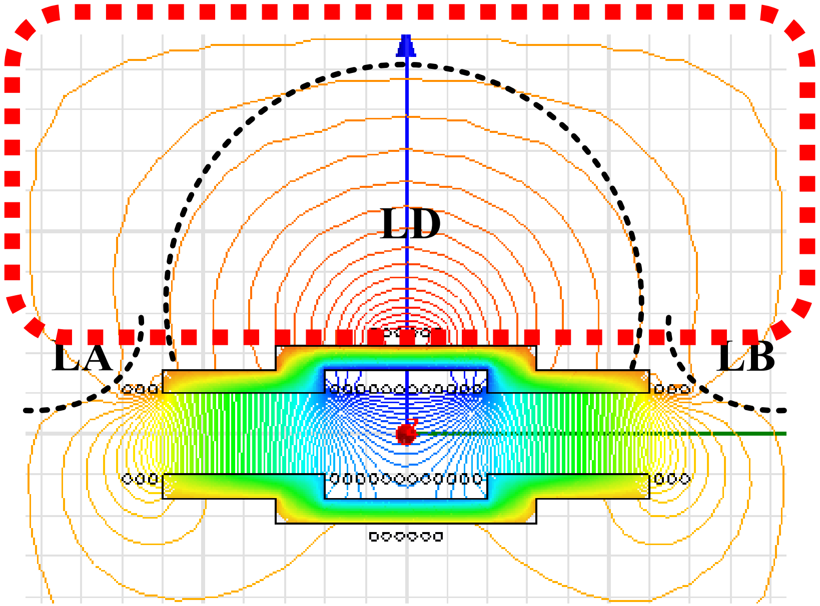


PLUS

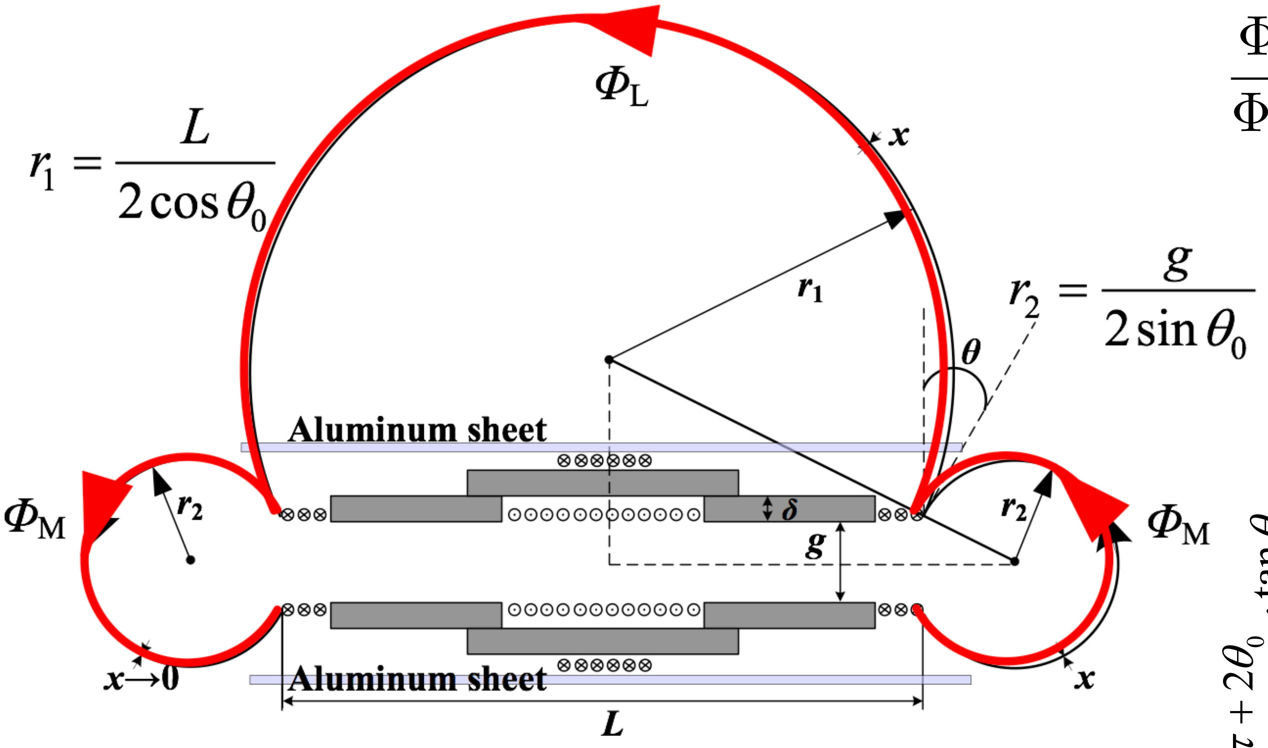


Added winding



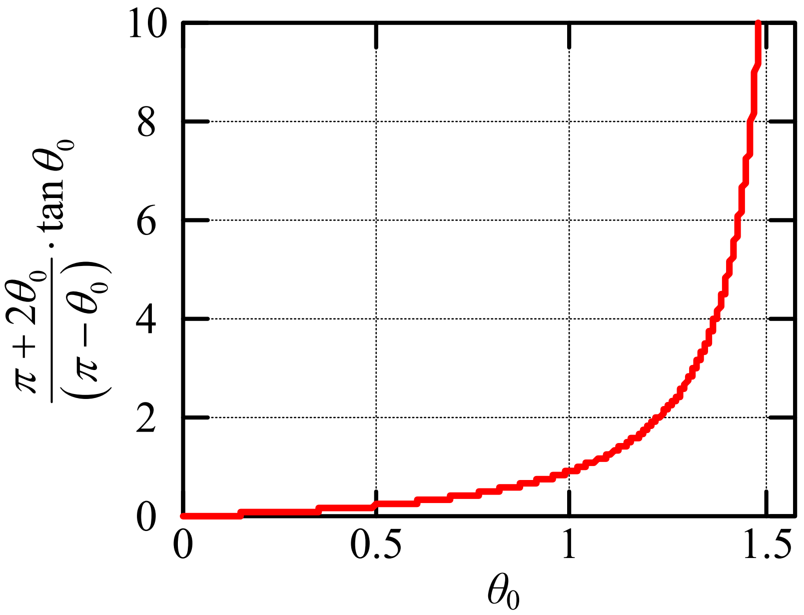


Shielding Enhancement

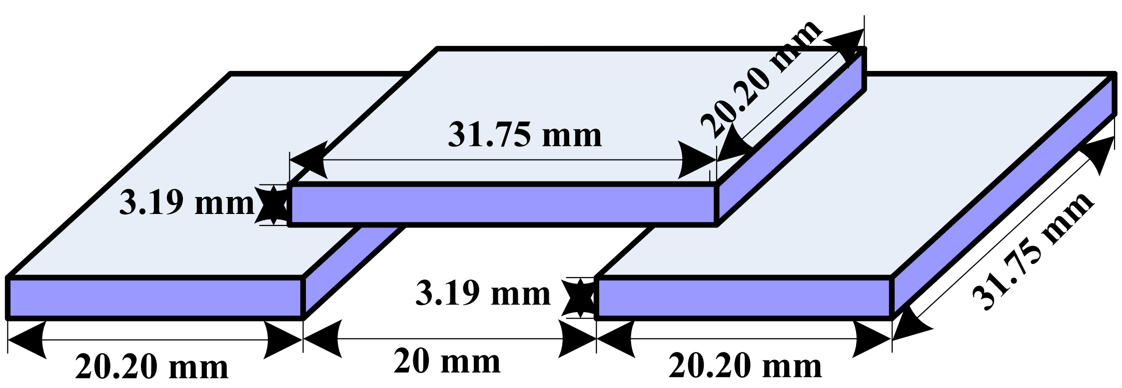


$$\frac{\Phi_{\text{av\_L}}}{\Phi_{\text{av\_M}}} = \frac{\pi + 2\theta_0}{4(\pi - \theta_0)} \tan\theta_0 \left(\frac{L}{g}\right) > 1$$

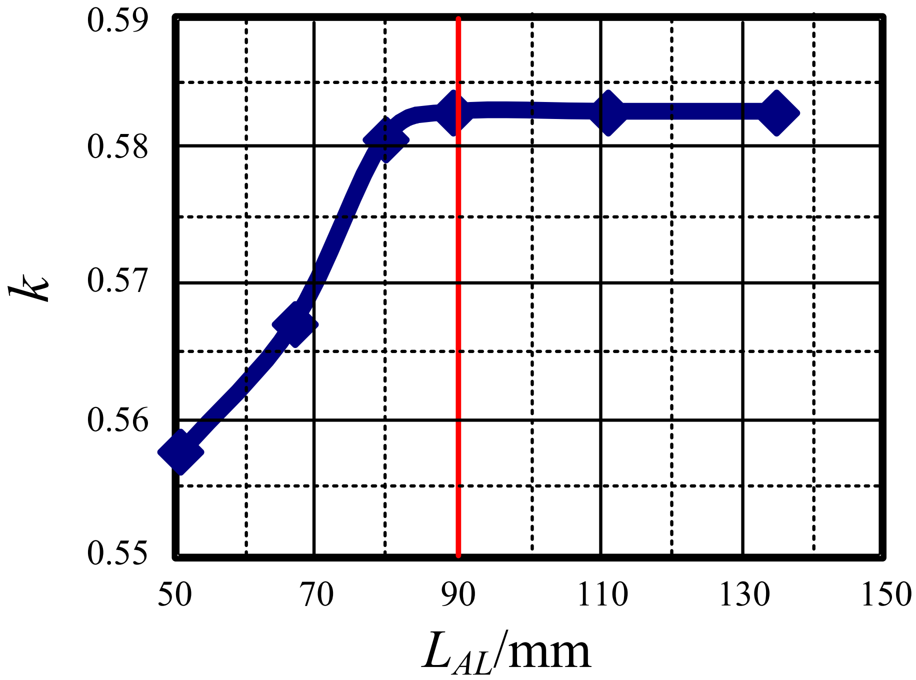
$$\frac{\pi + 2\theta_0}{(\pi - \theta_0)} \cdot \tan\theta_0 > \frac{4g}{L}$$



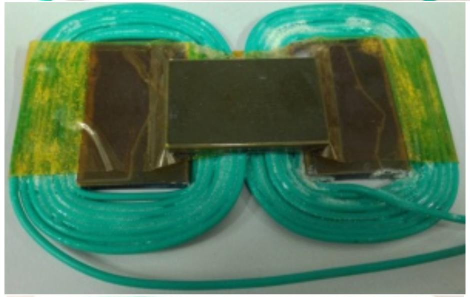
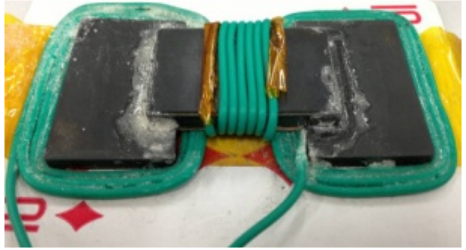
Experimental Results



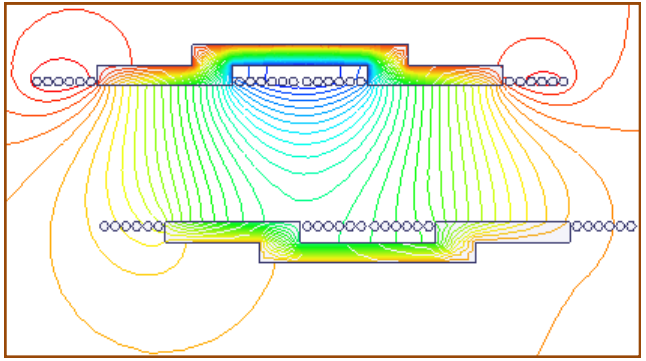
$$L_{\mathrm{Al}} \geq L + 2(2\delta + d)\tan\theta_0$$

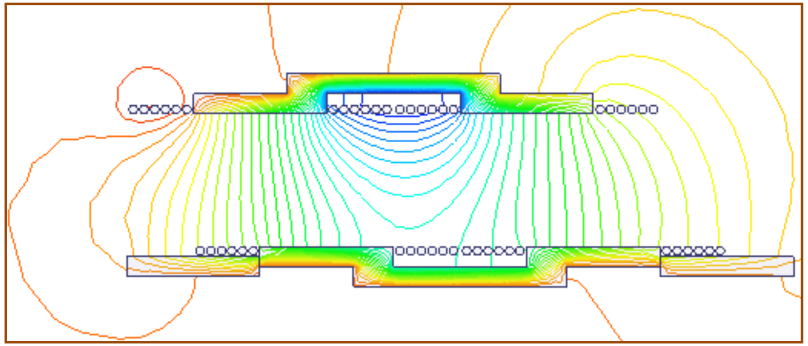


Experimental Results

	TRANSFORMER PHOTOS	L (mm)/ g (mm)	k
Vertical winding		330/50=6.6	0.48
Planar side winding		90/10=9	0.523
Combined winding		73/10=7.3	0.583

Extended U-core Misalignment



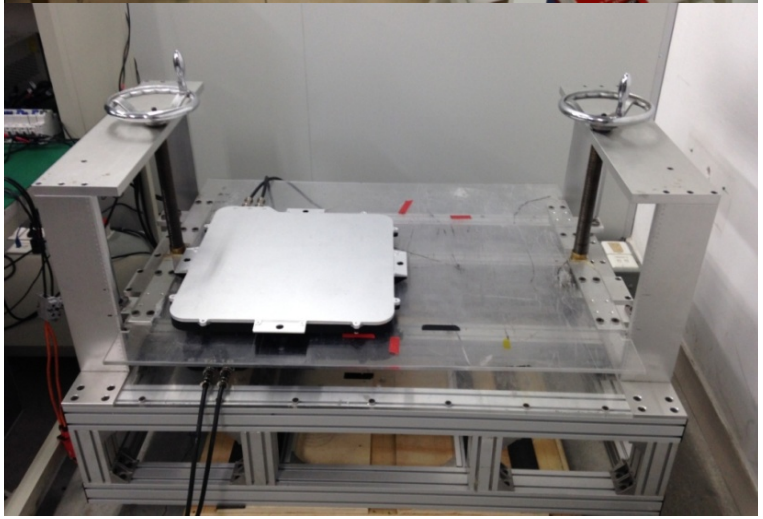


1kW System Efficiency	Gap 20 cm Perfectly aligned	Gap 26 cm Perfectly aligned	Gap 26 cm Displaced 14 cm
Tranditional U-core	91.25%	87.59%	81.67%
Extended U-core with combined windings		88.14%	82.75%

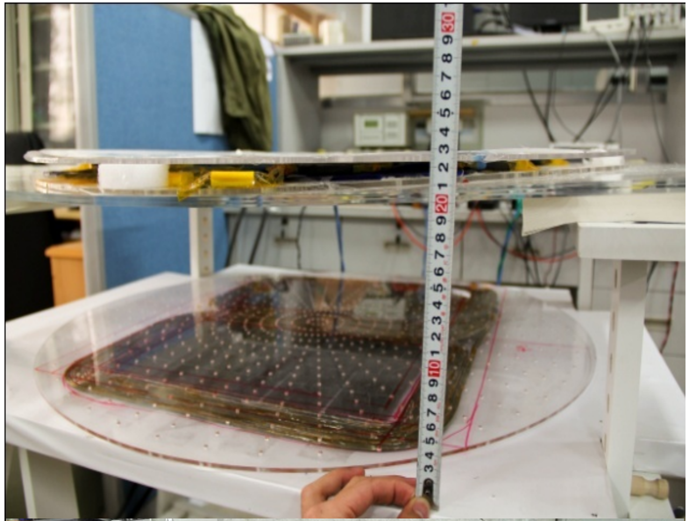
NUAA Collaborator's Lab at Nanjing

Prof. Qianhong Chen

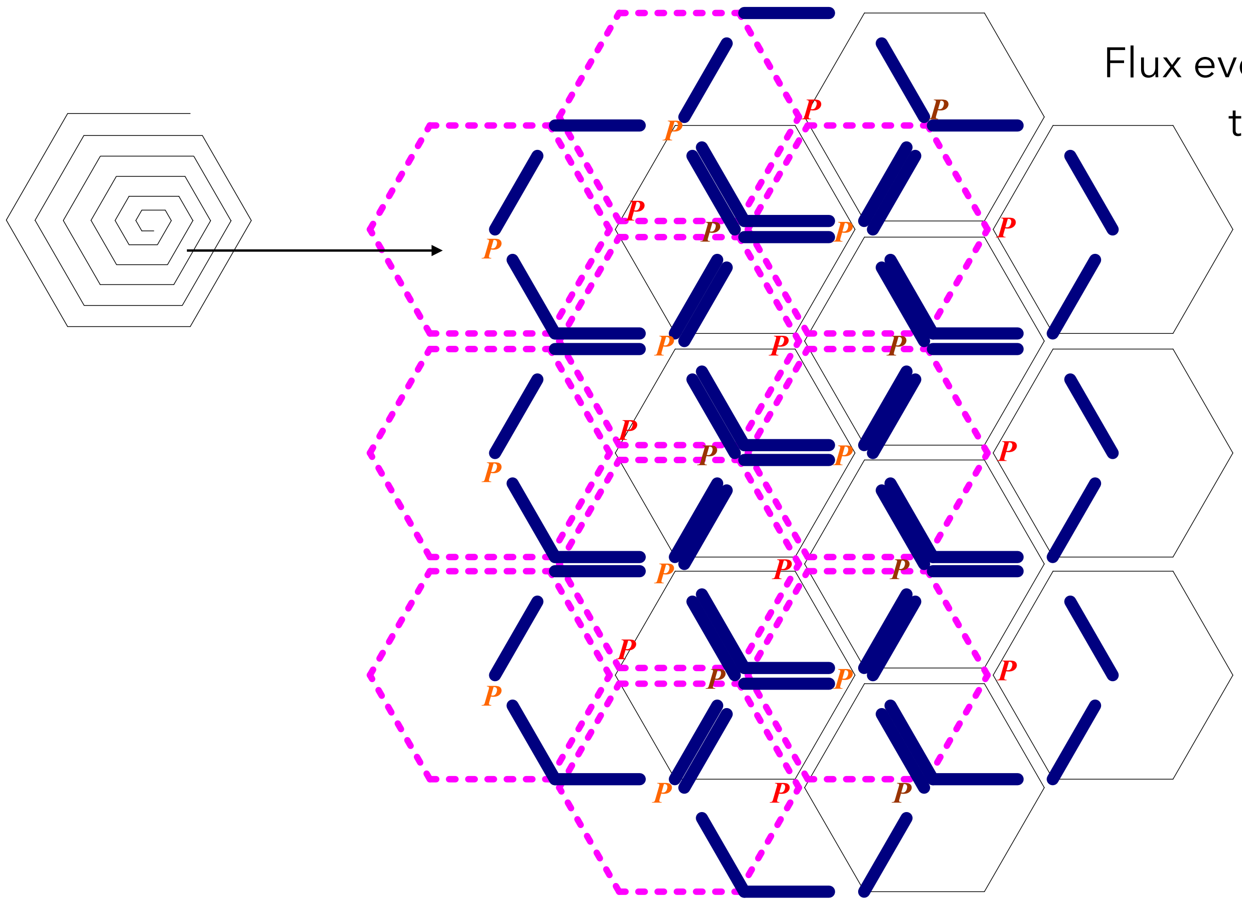
5 kW



30 kW



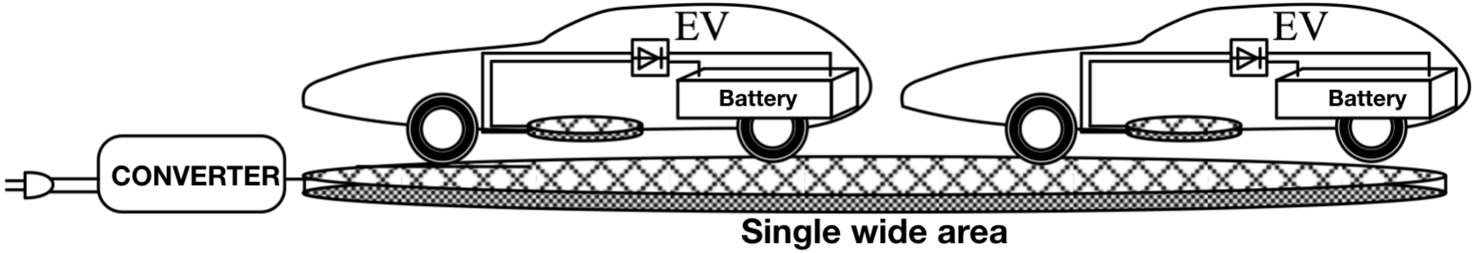
3-layer PCB windings



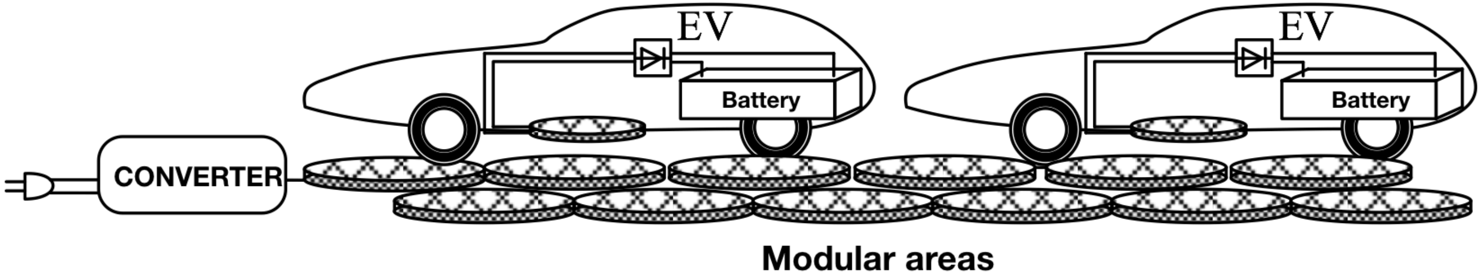
Flux evenly distributed over the entire area

Sectional charging pads

Wide area coverage

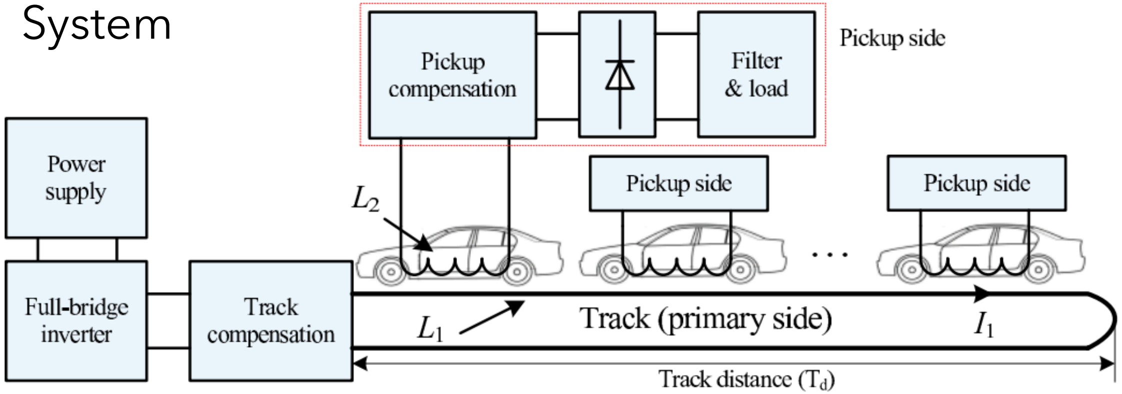


Cost and material reduction, still covering wide area

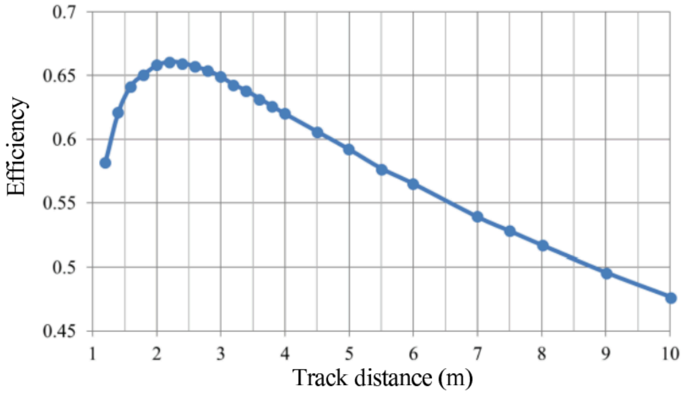


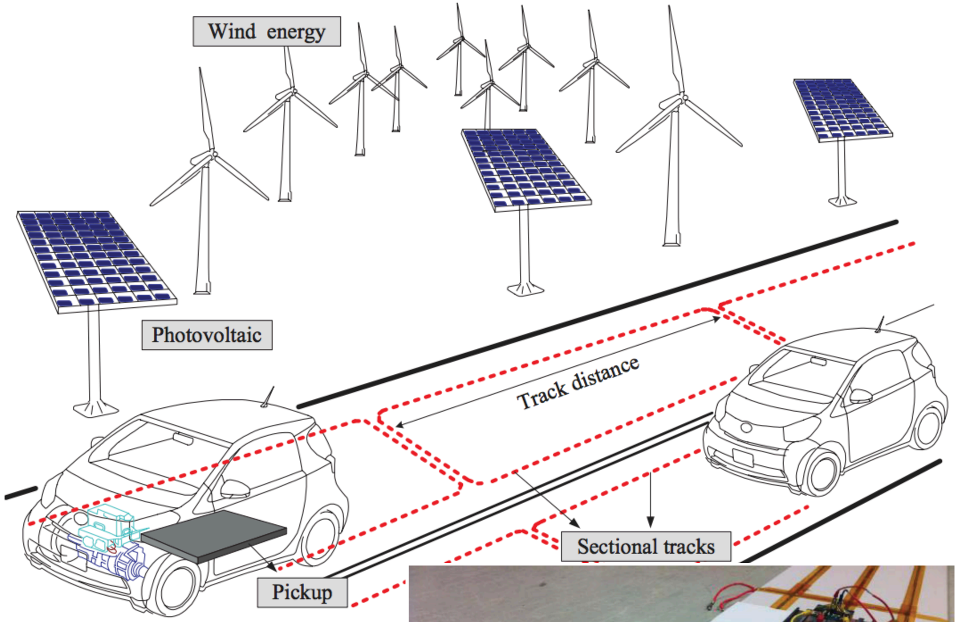
Roadway charging

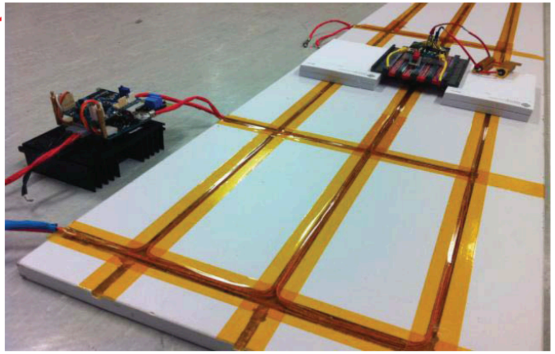
Sectional Tracks in Roadway Inductive Power Transfer System



Analysis for moving vehicles charging system, multiple vehicles sharing power, distance, etc.







W. Zhang, S. C. Wong, C. K. Tse, and Q. Chen, "An optimized track length in roadway inductive power transfer systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 2, no. 3, pp. 598–608, September 2014.

Interim Conlusion

- So far, the circular pads are still the most popular.
- DD, DDQ pads are receiving significant attention as they can increase coupling capability.
- Lots of results have been obtained mainly from EXPERIMENTAL studies.
    - Coupling
    - Misalignment
    - Efficiency
    - Cost
- Analysis is possible, but not very comprehensive due to the complex geometry and flux interaction. A conventional EM field.
- New core geometries and winding arrangements will continue to emerge in the coming years. Lots of opportunities for research.