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Wireless power Transfer: Introduction and History

Tutorial

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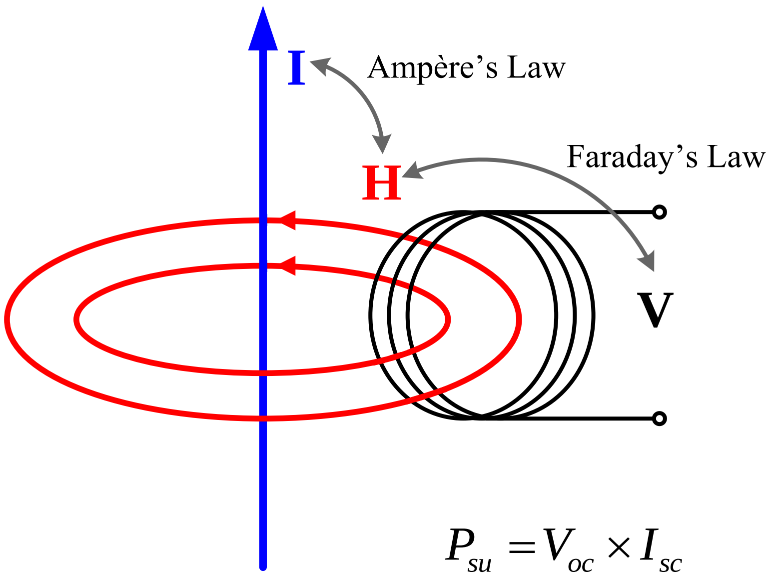
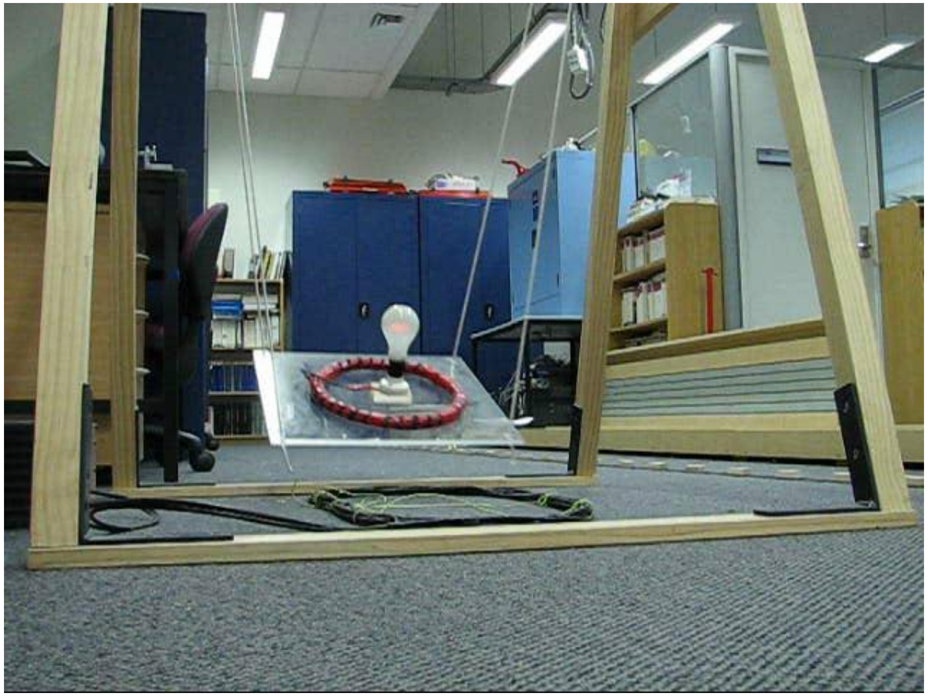
Overview

- Wireless Power Transfer History: A Brief History
- Fundamentals of WPT
- Development at U.o.A.
- Development of Track Magnetics
  - Achieving Greater freedom
- Development of Lumped Charging Applications
  - Charging Pads for EVs
  - Non-polarised Couplers
  - Polarised Couplers
- The Future?

Wireless Power Transfer (WPT)





- The transfer of electrical power from one system to another, without wires.
- Reliable
- Tolerant of water, chemicals, and dirt.
  - But regarded as impossible for 200 years

WPT HISTORY

Brief Historical Overview of Near field WPT

- 1894 Hutin & Le Blanc (proposed power to rail conductors)
- 1890s-1920s Tesla (CPT and WPT tuned resonant coils)
- 1960-70s Biomedical Applications with resonant coupling
- 1974-75: Otto (NZ), Bolger (US) propose roadway power
- 1980s: Bio-implants, Guided Roadway projects (Santa Barbara project), aircraft entertainment
  - uncontrolled or detuning controllers
- 1990s: Industrial applications in materials handling, Robotics and People mover systems (including buses)
  - fully independent decoupling controllers
- 2000s: Planar electronics, Cellular phone applications, heart pumps, Commercial bus systems
- 2010s: Private electric vehicle stationary charging trials, light rail and buses powering on the move

References [1]-[9]

Wireless Power Transfer History

Fig.5

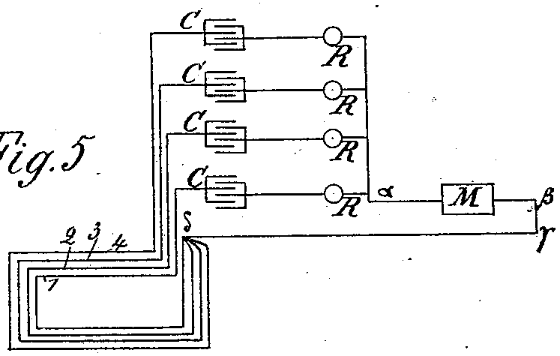


Fig.3

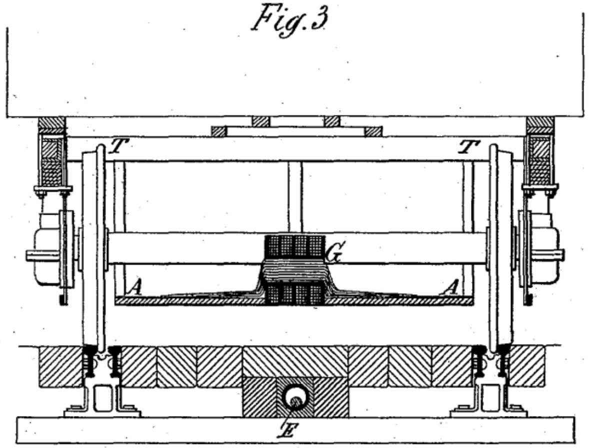
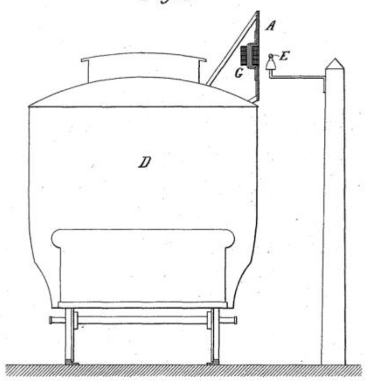


Fig. 8.

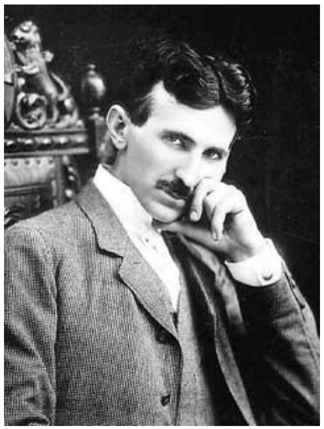


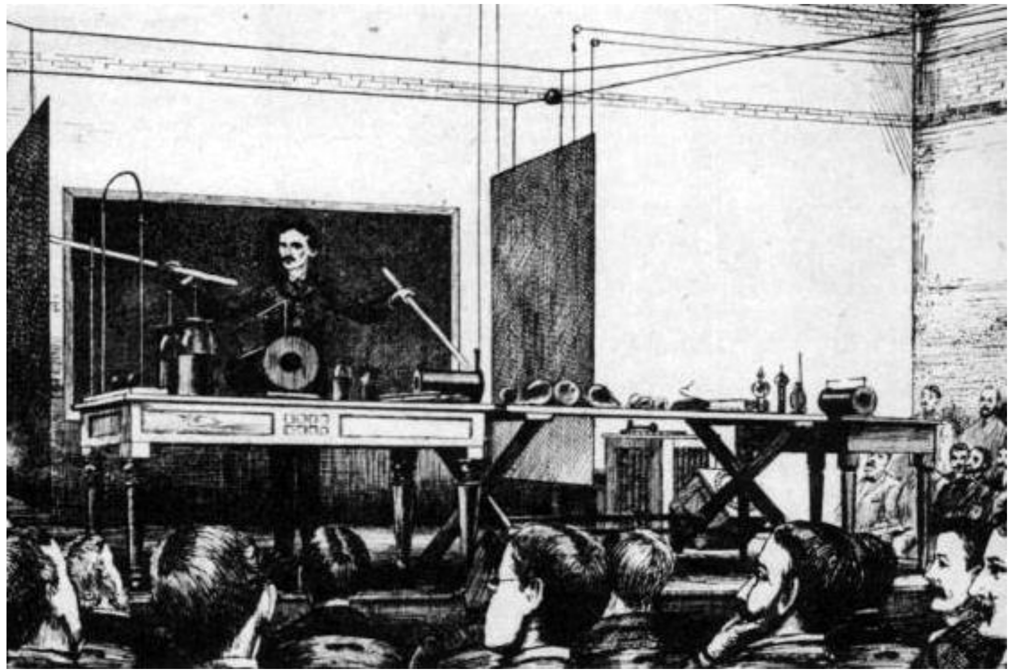
"Transformer System for Electric Railways"

- Proposed inductive moving railway vehicles on rail conductors
- 1-2kHz track frequency
- Capacitive compensation of pick-up
- Multiple pick-ups used for various power ratings
- Could only transmit signals

1894 - Hutin and LeBlanc US patent 527857

Wireless Power Transfer History





Teslas Capacitive Power Transfer (CPT) demo in 1891 [1]

- Nikola Tesla

A "world system" for "the transmission of electrical energy without wires"

Reference [1,3]

A Sceptical Background:

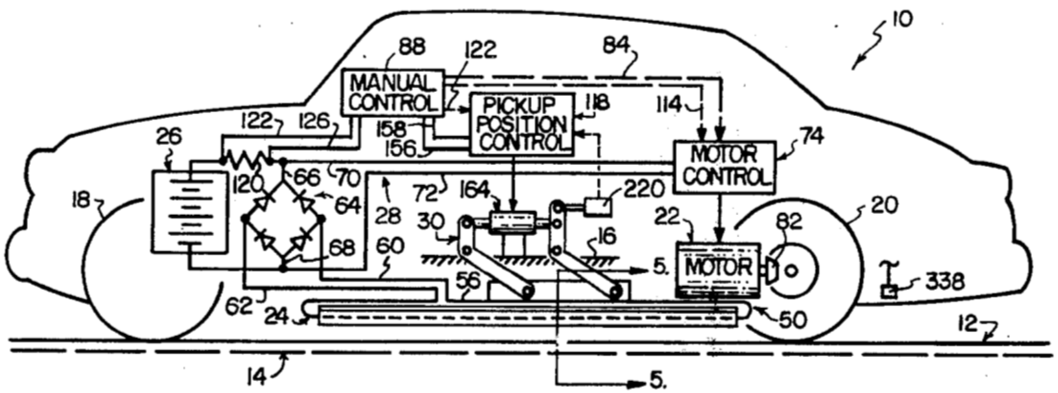
- "Inductive Power Transfer cannot be done" (Jervis Webb):
  - Signals: Yes
  - Tooth-brushes: Yes
  - Real Power: No!

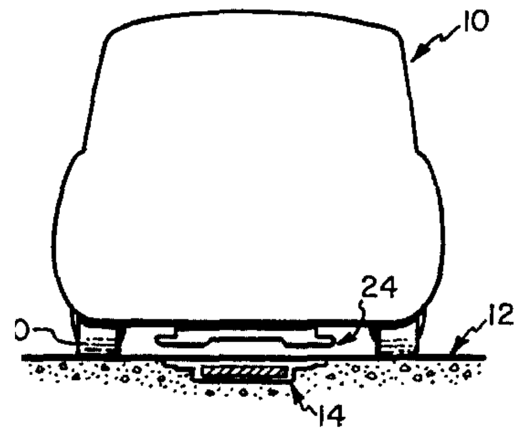
- But made possible because of
  - power electronics,
  - resonant circuits,
  - electromagnetics
  - innovations
    - Control and stability (protection from bifurcation)
    - Highly efficient systems (electronics and magnetics)

Wireless Power Transfer History

1975 - Bolger

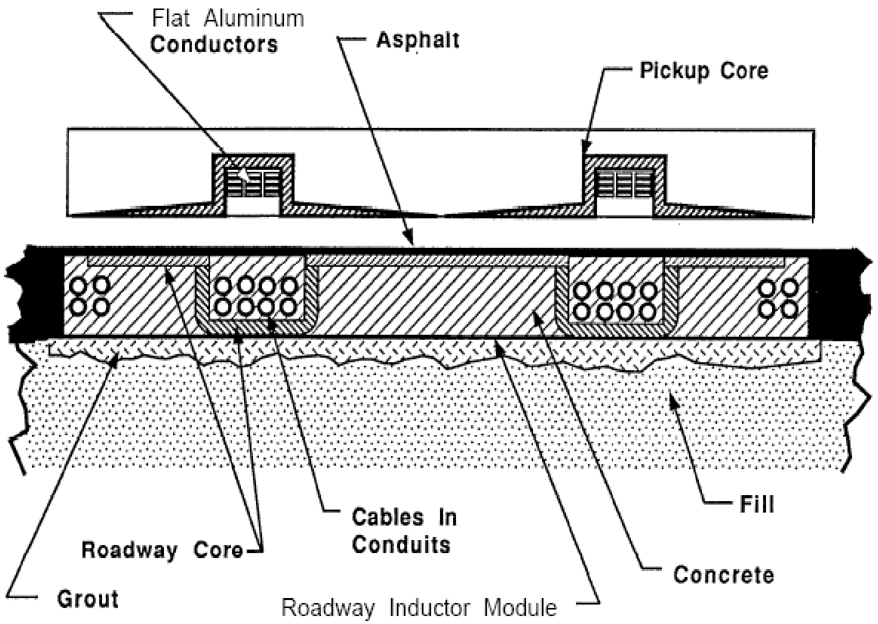
US Patent 3914562 “Supplying Power to Vehicles”





- Pickup mechanically raised and lowered
- First system technically feasible

Santa Barbra Project

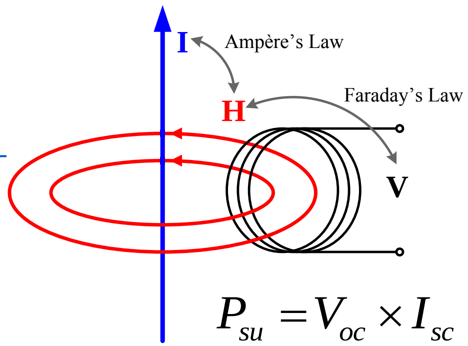


- Roadway Powered Electric Bus (1980~1996)
  - Low efficiency, gaps 5-7cm
  - Secondary 1mx4.3m, 7.5kg, variable tuning
  - High construction cost : 0.74 ~ 1.22 M$/km

Reference [2]

WPT FUNDAMENTALS

Fundamentals of WPT



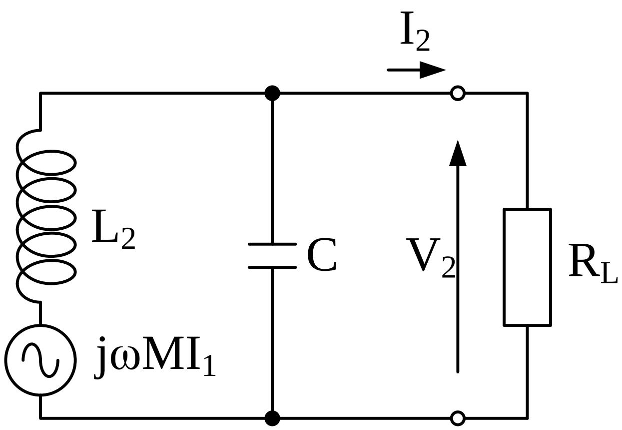
$$P_{su} = V_{oc} \times I_{sc}$$

- The two observables in the coupled coil cannot be observed at the same time
  - The Open Circuit voltage: $V_{OC} = j\omega M I_1$
  - The Short Circuit Current: $I_{SC} = I_1 M / L_2$
- Un-tuned VA Coupled into the secondary coil L_2:

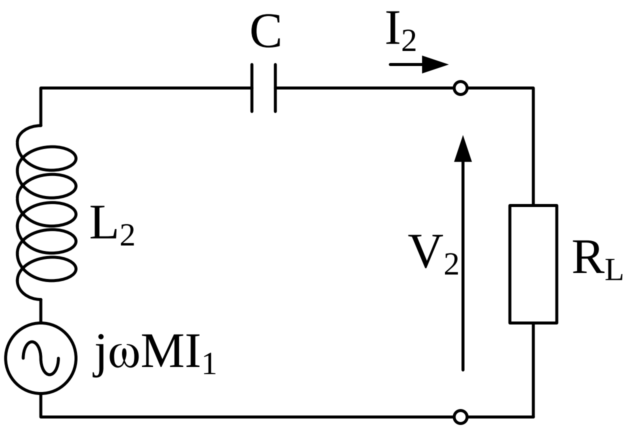
$$P_{su} = V_{oc} I_{sc} = \omega I_1^2 \frac{M^2}{L_2}$$

M is the mutual inductance between the track and the secondary coil

Why Secondary Tuning?



Parallel Tuned
Acts like a current source



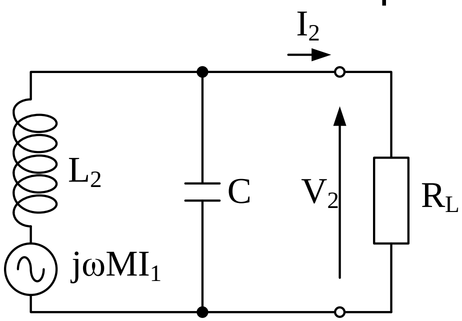
Series Tuned
Acts like a voltage source

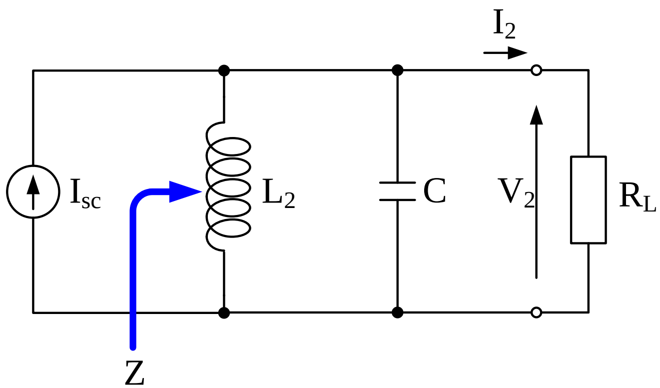
- To increase the power
- Tune at the track frequency

$$\omega_0 = 1/\sqrt{L_2 C} = \omega$$

The Effect of Tuning

Parallel tuned example

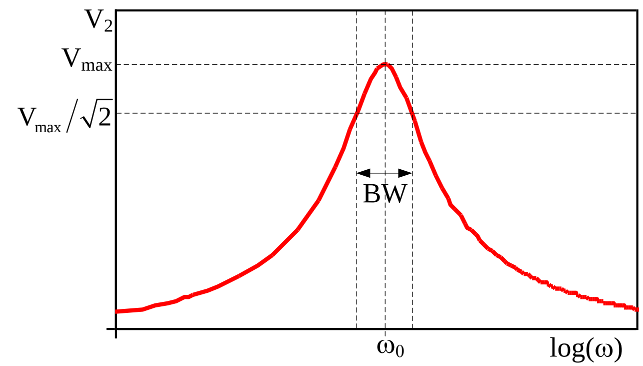




$$V_2 = I_{sc} Z = \frac{I_{sc} \frac{1}{C_2} s}{s^2 + \frac{1}{R_L C} s + \frac{1}{L_2 C}}$$

c.f. with second order band-pass filter

$$H(s) = \frac{H_0 \frac{\omega_0}{Q_2} s}{s^2 + \frac{\omega_0}{Q_2} s + \omega_0^{\,2}}$$



Maximum power point

$$\left|V_2\right|_{s=\omega_0} = \left|\frac{I_{sc} Q}{C\omega_0}\right| = \left|I_{sc}\omega_0 L_2 Q\right| = \left|Q V_{oc}\right|$$

$$Q_2 = \frac{1}{\omega_0 C R_L} = \frac{\omega_0 L_2}{R_L}$$

$$BW = \omega / Q_2$$

Secondary Tuning Impact on Primary

$$Z_r(\omega = \omega_0) = \begin{cases} \dfrac{\omega_0^2 M^2}{R_L} + j\omega_0 \Delta L_1 & \text{series tuned} \\ \dfrac{M^2}{L_2^2}\left(R_L - j\omega_0 L_2\right) + j\omega_0 \Delta L_1 & \text{parallel tuned} \end{cases}$$

Under ideal perfectly tuned secondary

Tuning Summary

- Tuning boosts power by circuit Q_2: $P_o = P_{su} Q_2$
- But secondary VA also increases: $VA \approx P Q_2 = P_{su} Q_2^2$
- And circuit bandwidth decreases: $BW = \omega_0 / Q_2$
- Reflected impedance onto the primary is:
  - Load dependant
  - Tuning dependant

The Tuned Output Power

$$P = V_{oc} I_{sc} \cdot Q_2 = \omega I_1^2 \cdot \frac{M^2}{L_2} \cdot Q_2 = V_1 I_1 \cdot k^2 \cdot Q_2$$

Dependent on:

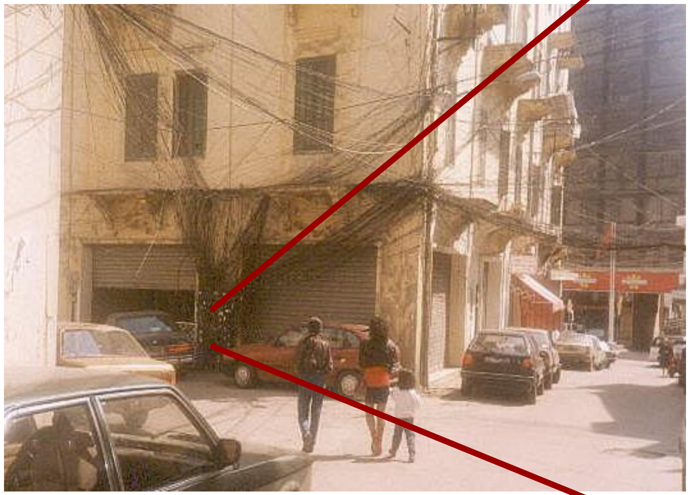
- Frequency
- Track current
- Magnetic Coupling
- Secondary Circuit Loaded Tuning Factor

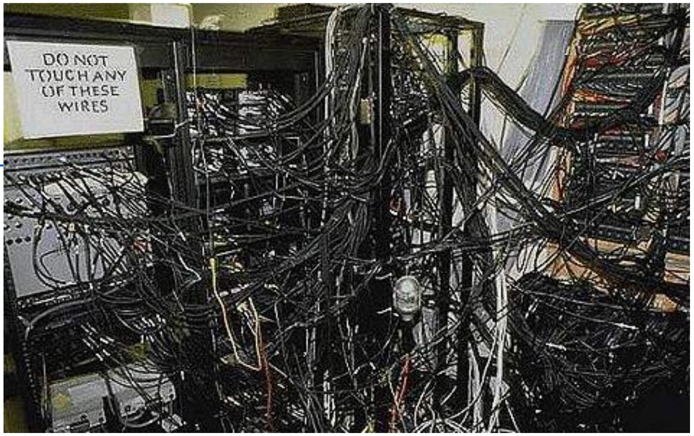
Reference [2,10]

DEVELOPMENT AT UOA

References [1]-[10]

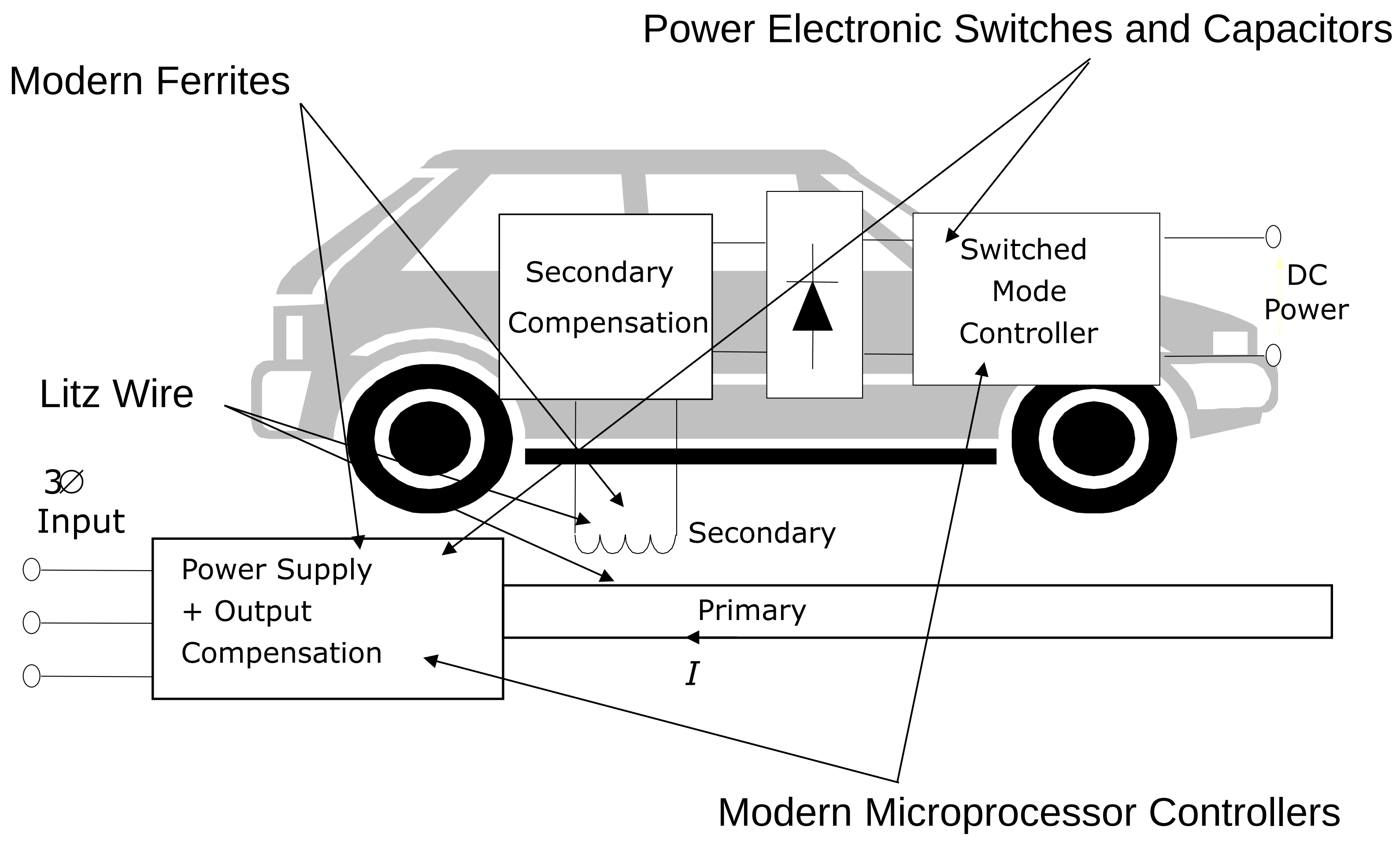
Motivation





Wires are messy & insecure

Reliant on Latest Technologies



Our Vision

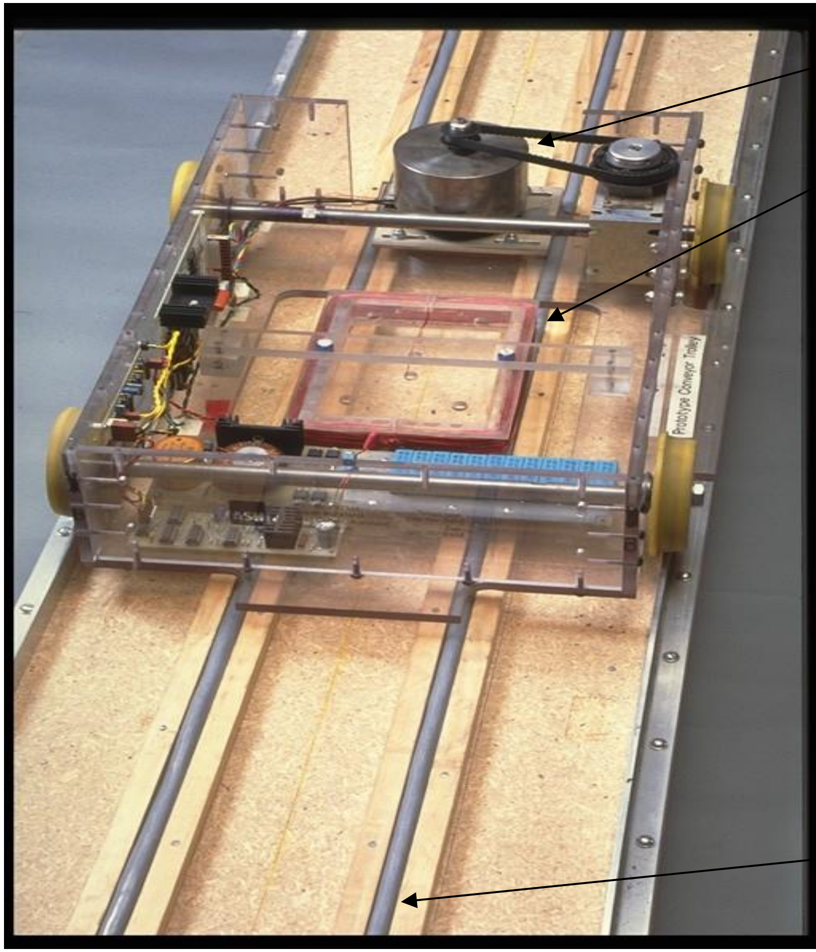
- WPT which is controllable, safe and efficient
  - Field shaping methods operable over a wide frequency range and applications
  - Systems with low leakage
  - Highly efficient
    - High quality factor components
    - Operating quality factors that ensure they are less sensitive to the environment
  - Controlled operation under highly resonant conditions

Moving platforms – a first step

Motivation

- Galvanic isolation
- Unaffected by dirt, water, chemicals
- Particularly clean – producing no residues
- No trailing wires
- No sliding brushes
- Maintenance free

1990: A first WPT System at the UoA.



Brushless DC Driving Motor

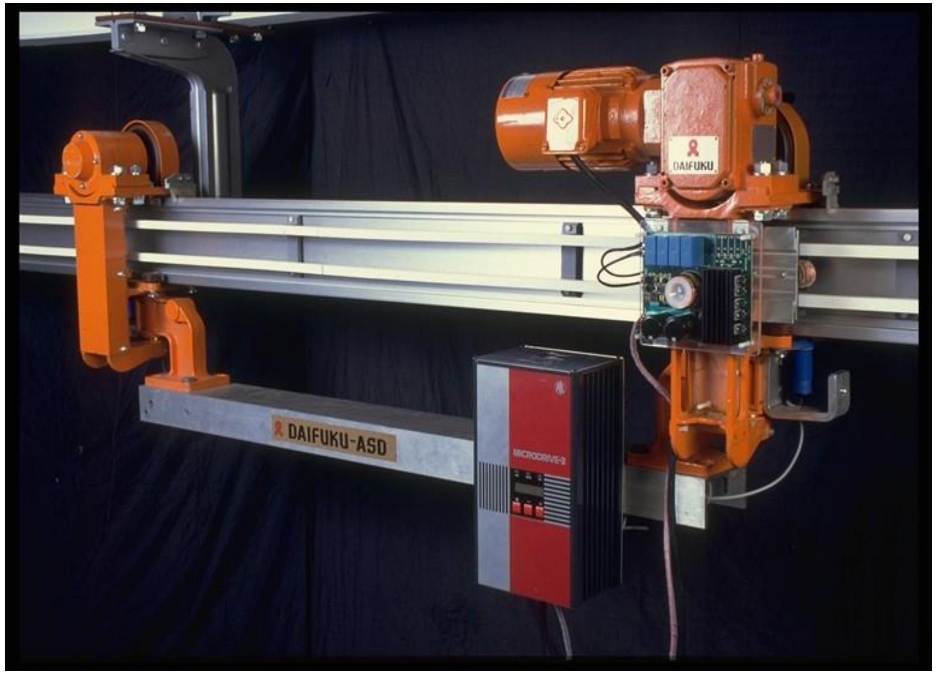
2mm Operating air-gap

100 pair telephone cables

- Alignment non critical
- No power regulation
- Maximum 1 trolley/track
- Large pick-up coil
- Low efficiency

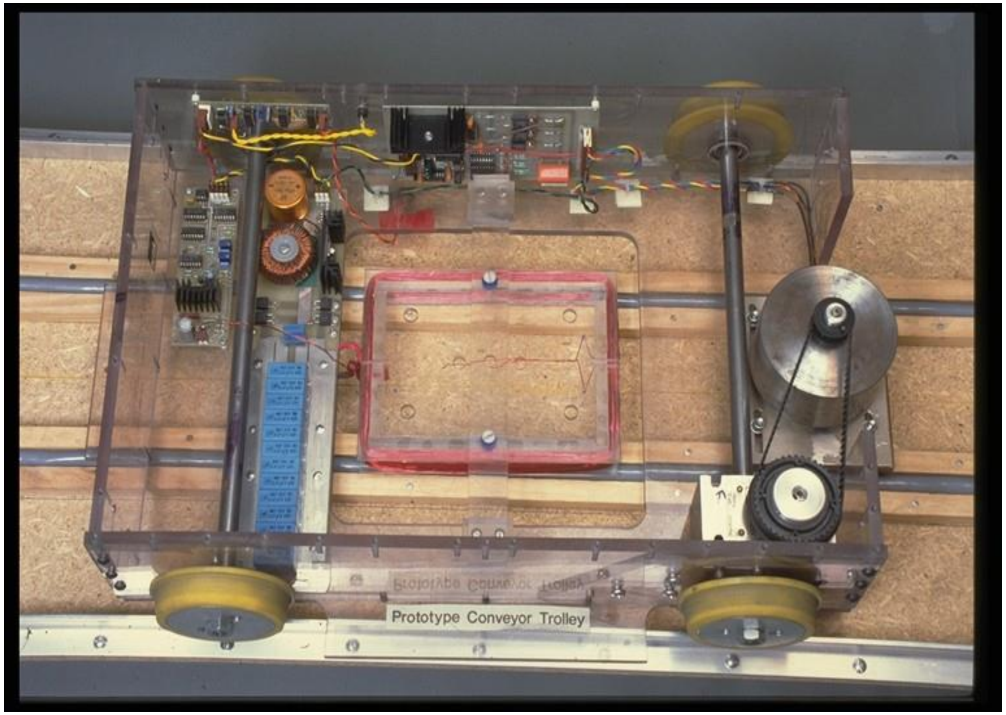
But it worked!!!

Daifuku wanted:



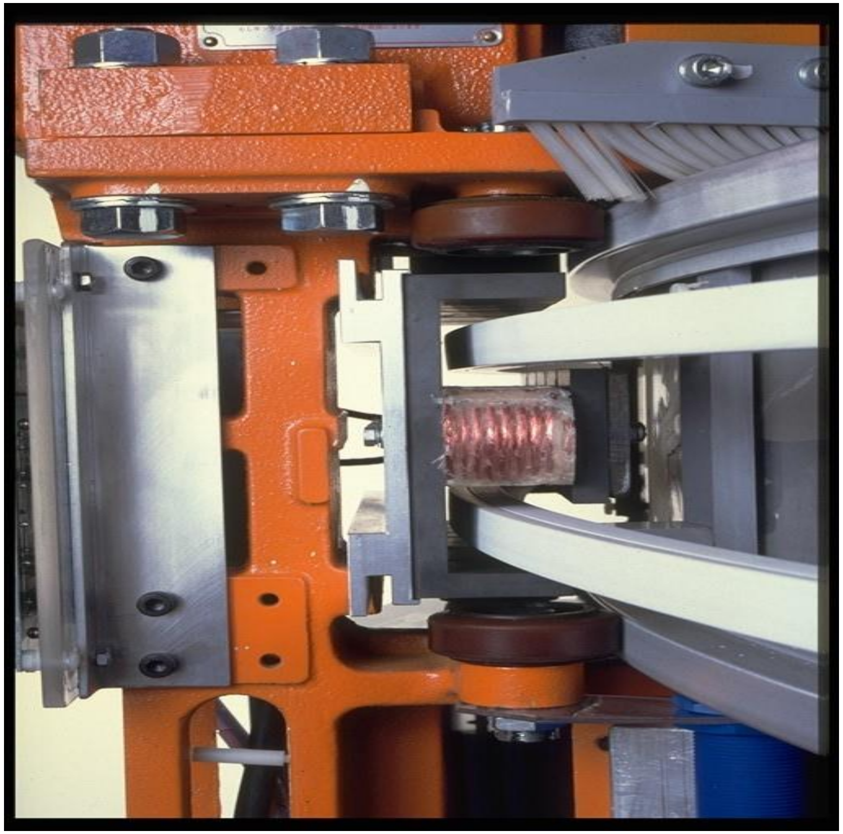
Power rating/secondary	> 200 Watts each, all independent
System Efficiency	> 75%
Delivery	< 4 Months
Special terms	Payment on completion Assistance with components

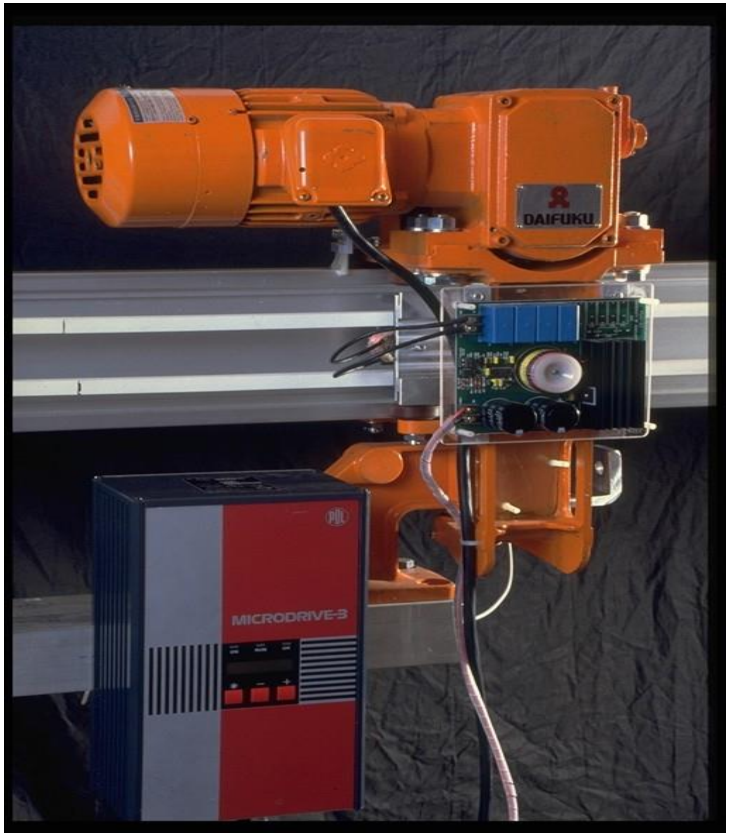
We had:



- 15 month old toy system
- No appreciation of the inherent difficulties
- No idea how to achieve independent secondary controllers
- 4 months to produce a working 3-trolley system!

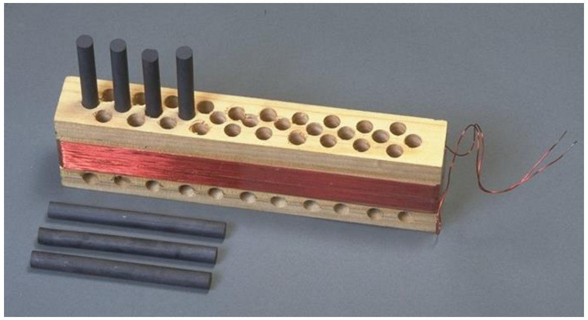
Pick-up & Controller: Mounted on Monorail



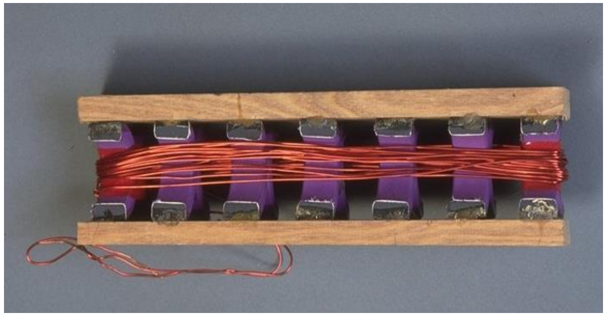


- Required New Secondary Magnetic Design
- New Approach to Control - Decoupling

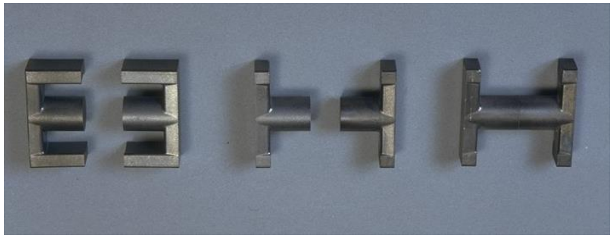
Pick-up development:



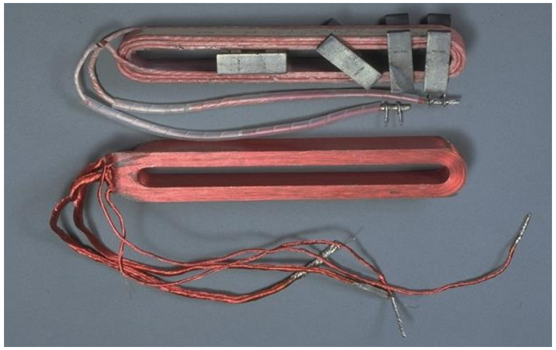
Wood and ferrite rods

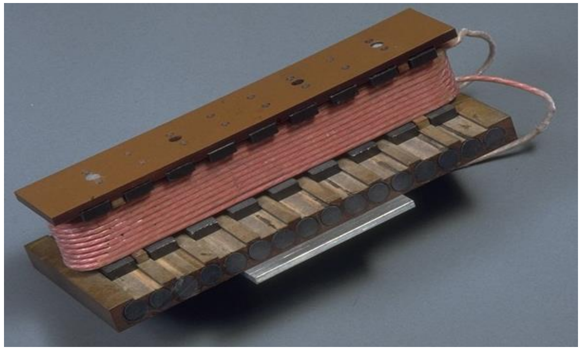


Cut Toroid's

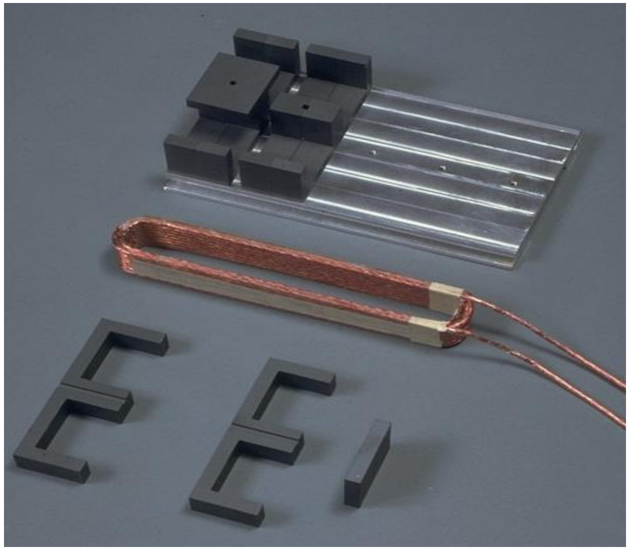


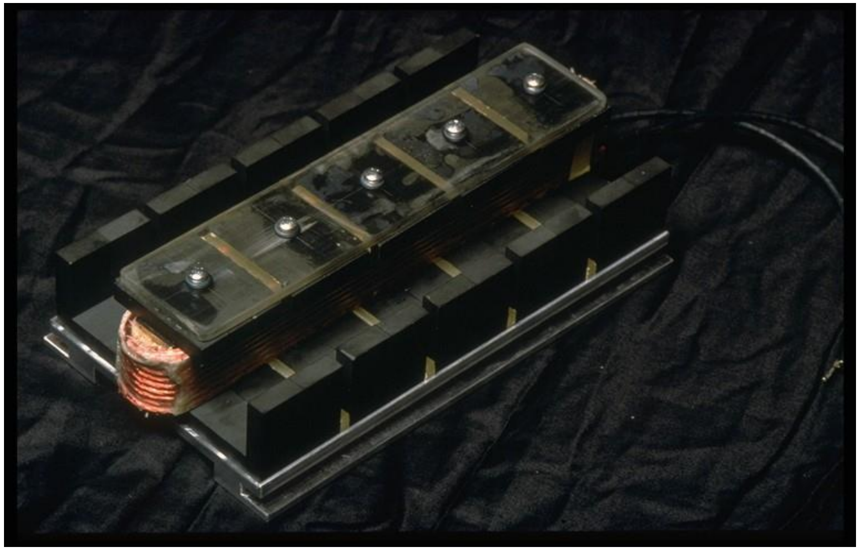
ETD-49 development





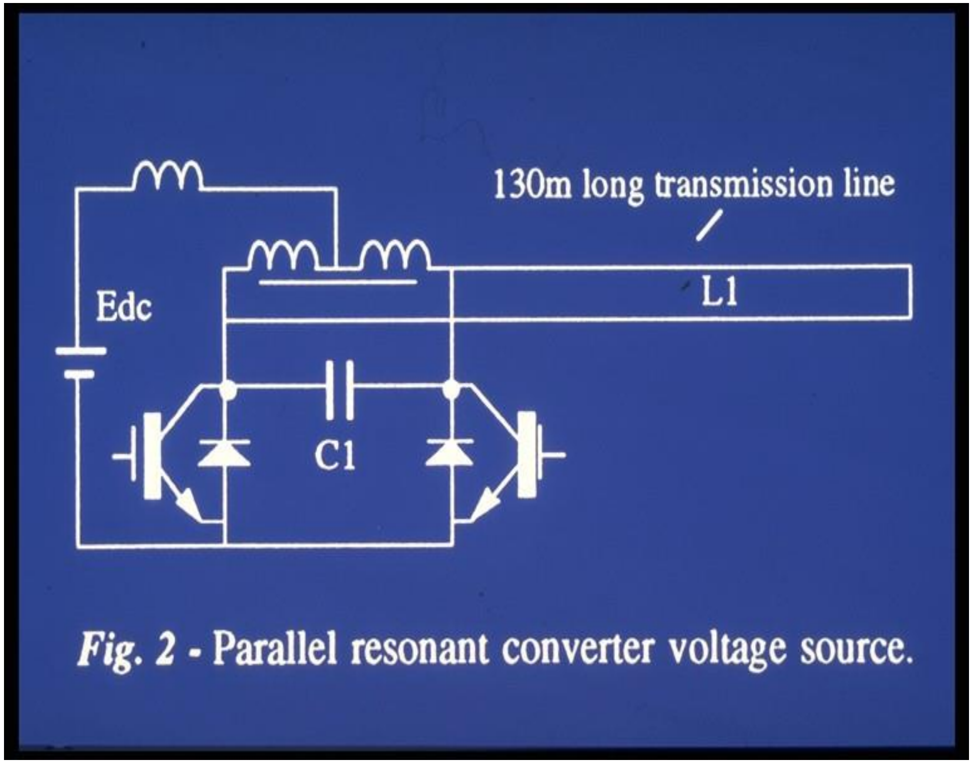
Final magnetic development





- Custom Ferrite system assembled

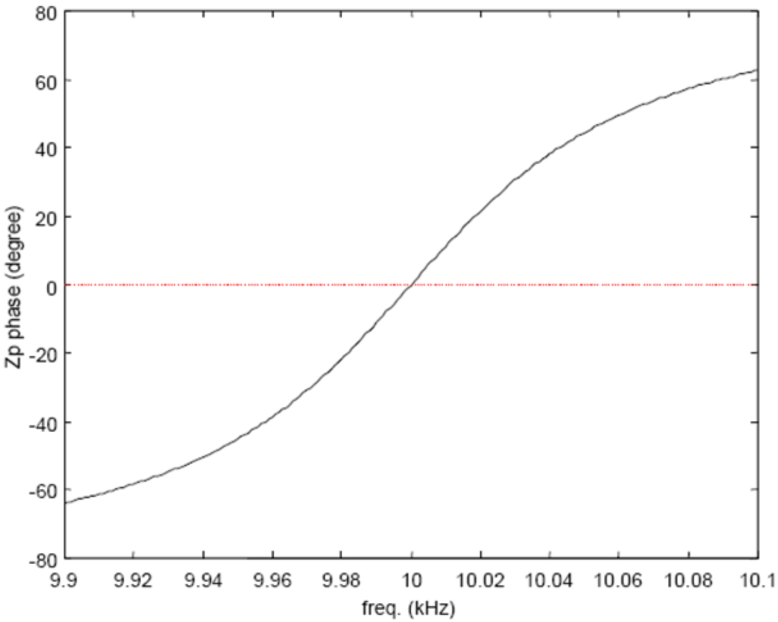
Early Load Resonant Supply



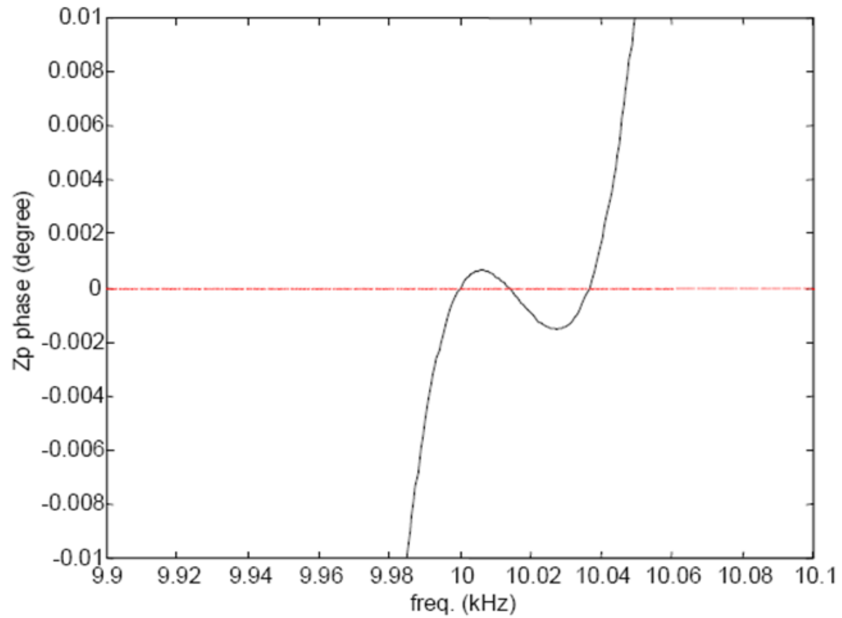
- Current sourced push-pull
- Supply frequency varies with changes in:
  - Tuning capacitor C_1
  - Track inductance L_1

Reference [10]

Frequency Stability Problem



Light Load

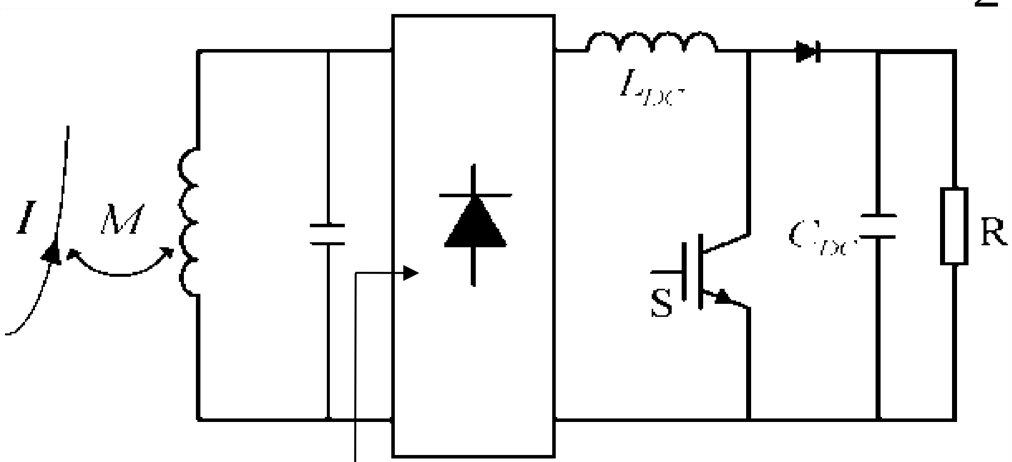


Heavy Load

- At heavy load there are two stable operating points.
- To avoid bifurcation total secondary VA < the track VA.

The First Decoupling Controller

$$P_o = \frac{\pi}{2\sqrt{2}} \cdot I_1 \frac{M}{L_2} \cdot V_o (1 - D)$$



$$R_L = \frac{8R}{\pi^2}(1-D)^2$$

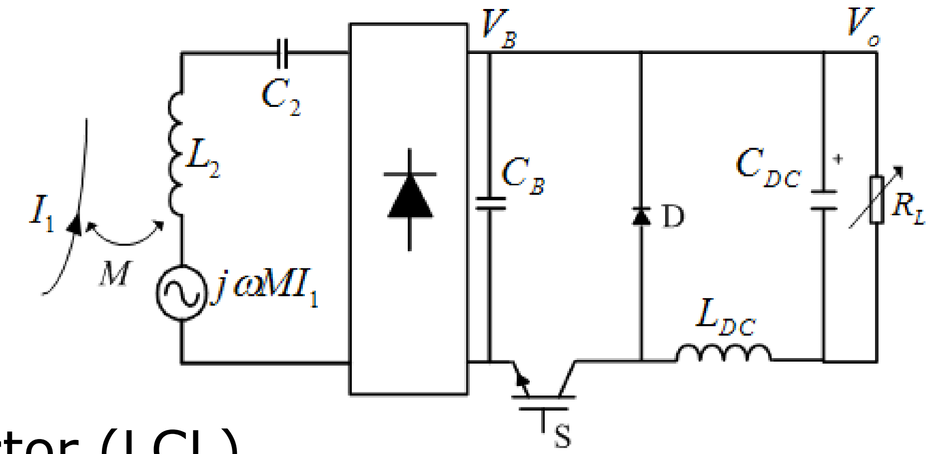
$$Z_r(\omega = \omega_0) = \frac{M^2}{L_2^2}\left(R_L - j\omega_0 L_2\right) + j\omega_0 \Delta L_1$$

- Enabled
  - independent load control using switch duty cycle ($0 \le D \le 1$)
  - Control of loaded Q_2

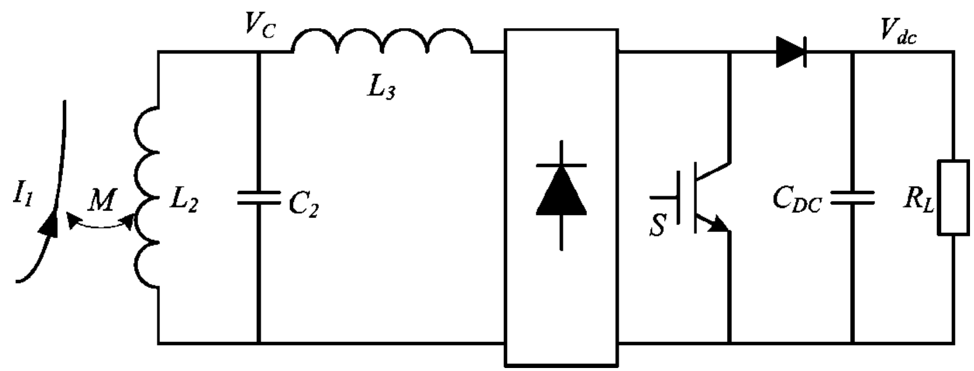
Reference [10]

Other Decoupling Controllers

- Series tuned

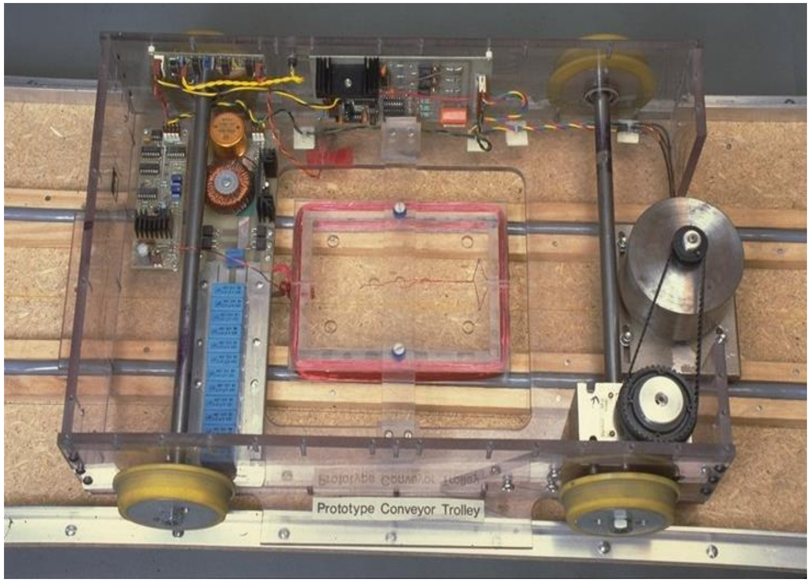


- Unity Power Factor (LCL)

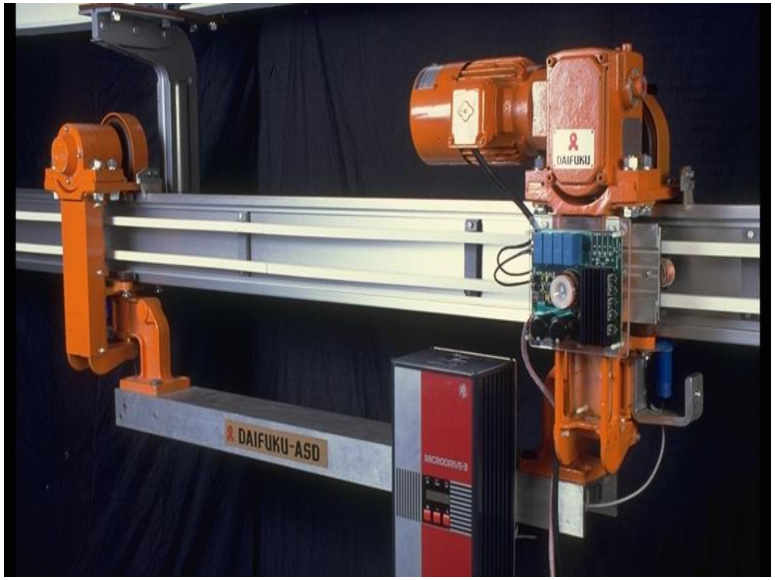


References [11]-[12]

Prototype Comparison



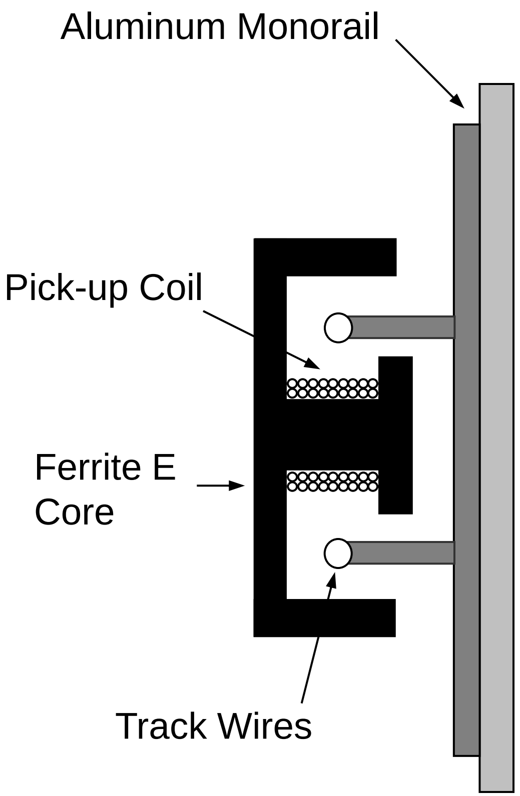
Original System



Daifuku Prototype

	Original System	Daifuku Prototype
Power rating	1W	400 W
Efficiency	<10%	85%
# of Carriers	1	3
Load	75 kg	250 kg
Speed	0.1 m/s	1 m/s
Track current	80A	80A
Track length	3 m	25 m
Air-gap	2 mm	4 mm

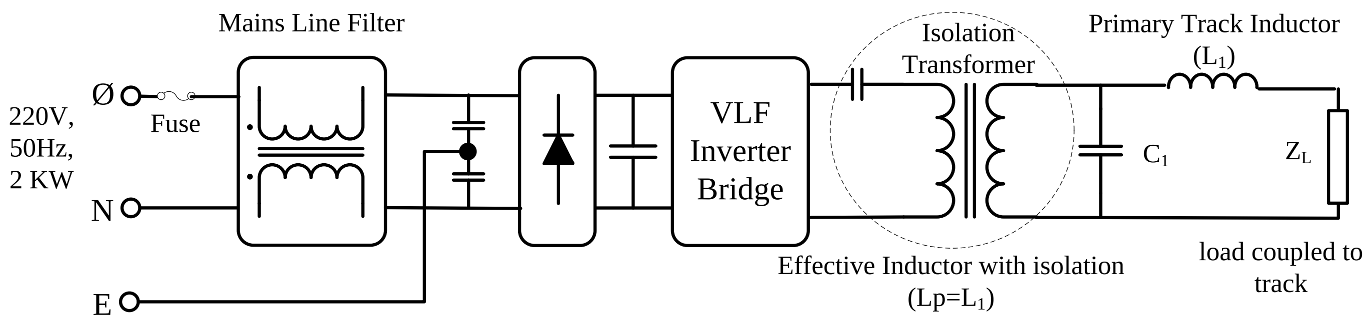
Prototype Operation



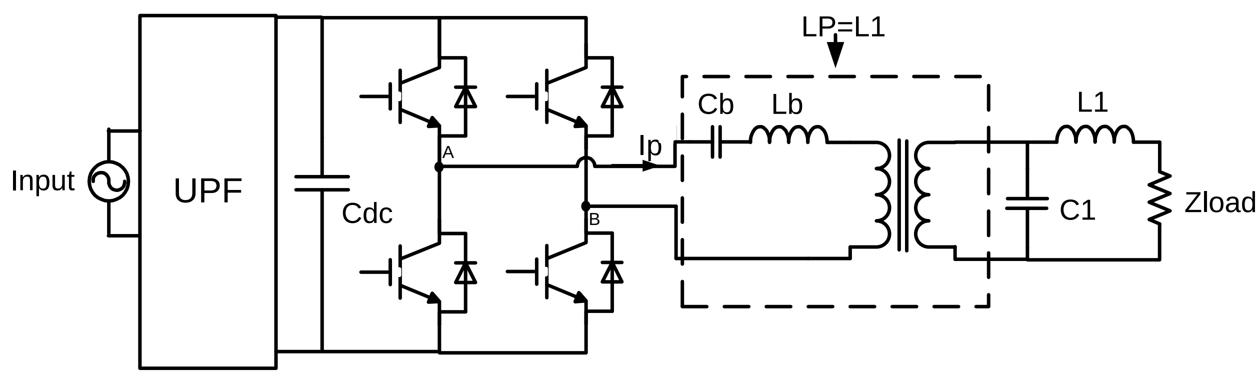
- Allowed movement
- Tolerant of misalignment.
- Unaffected by the environment

Fixed Frequency Supplies

- Single Phase LCL Topologies
  - Low energy bus



  - UPF input stage



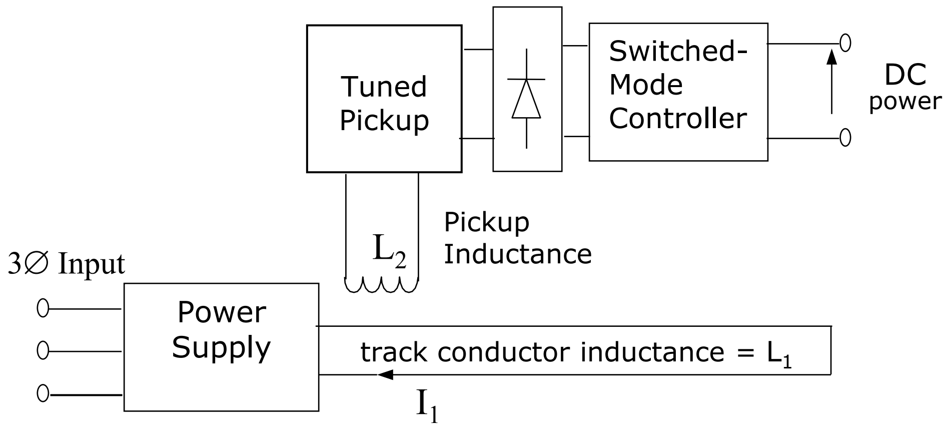
References [13]-[15]

DEVELOPMENT OF TRACK MAGNETICS

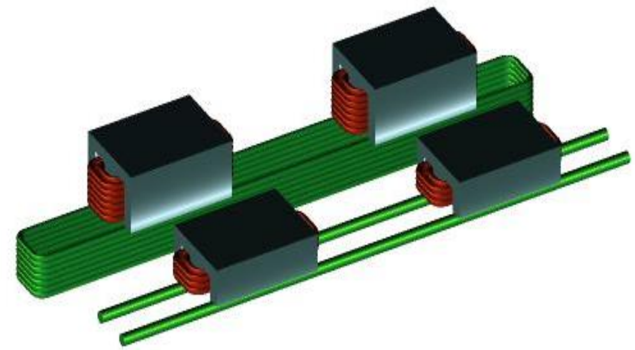
Track Systems 1990s

- Stationary and moving systems
- Guided mechanically on monorails (Materials Handling)
- Guided electronically above buried tracks (AGVs)
- History of trailing wires, brushed or mechanical chain and pulley
- Connections were a major problem
- Environments were very dirty or ultra clean.

System Operation

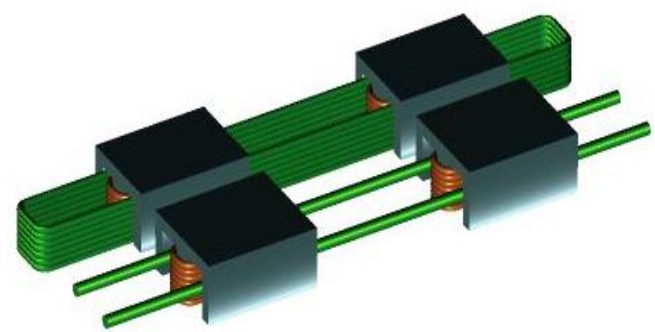


Individual k very low < 0.05



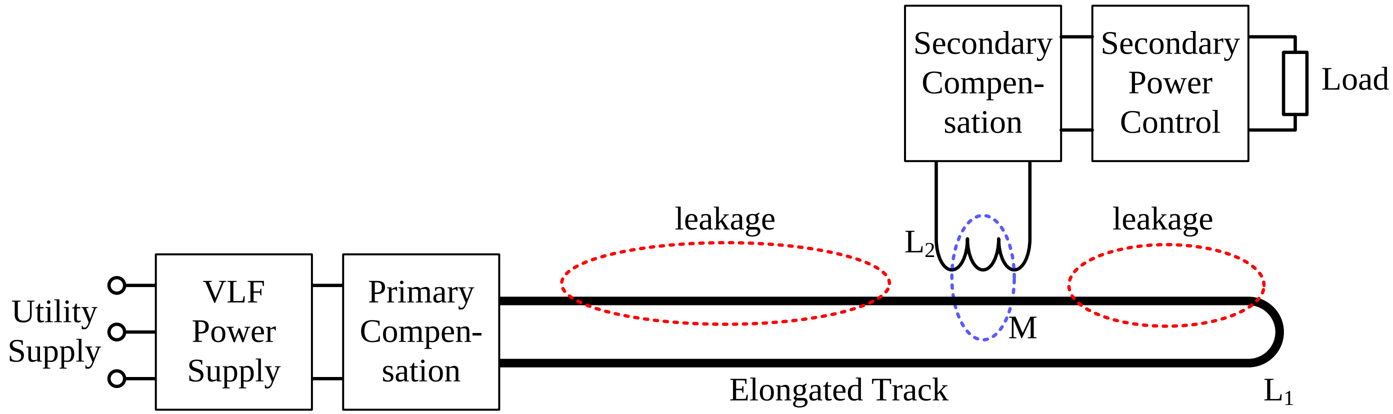
Primary recessed in floor: flat pick-ups

- Loosely coupled: $k < 0.05$
  - Supply Current sourced
    - Independent secondaries
    - Efficiency high under load (0 no load)
  - Often no primary core
  - Secondary may move



Rail mounted systems: E-core

Metrics for Multiple Secondary's



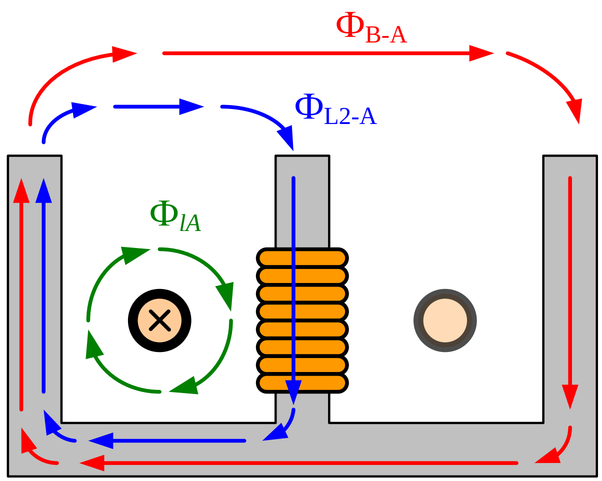
- k is a system co-efficient
  - Doesn't fairly represent how good the magnetics are
- Kappa looks at the coupling without leakage

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

$$\kappa = \frac{N_2}{N_1}\frac{M}{L_2} = \frac{N_2}{N_1}\frac{I_{sc}}{I_1} = \frac{\Phi_M}{\Phi_{L_2}}$$

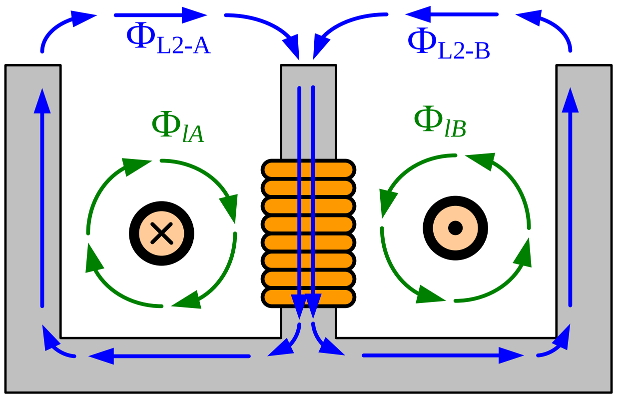
Reference [16]

Improving the Magnetic Design



Track Conductor A (excited)

Track Conductor B (not excited)



Track Conductor A (excited)

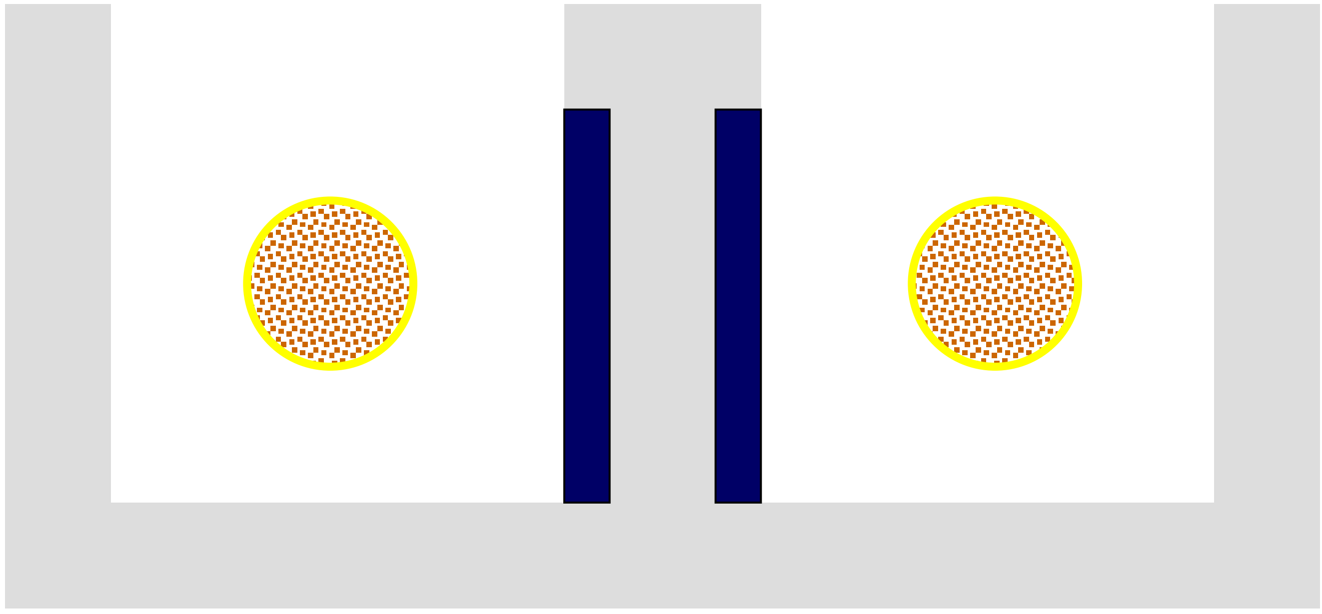
Track Conductor B (excited)

$$\Phi_{c\{A\}} = \Phi_{L2-A} + \Phi_{c\{B-A\}} + \Phi_{c\{lA\}}$$

$$ICCF = \frac{\Phi_{c\{B-A\}}}{\Phi_{c\{A\}}}$$

Problem: Flux Cancellation in E-Pick-up

Magnetic redesign: E to S Core

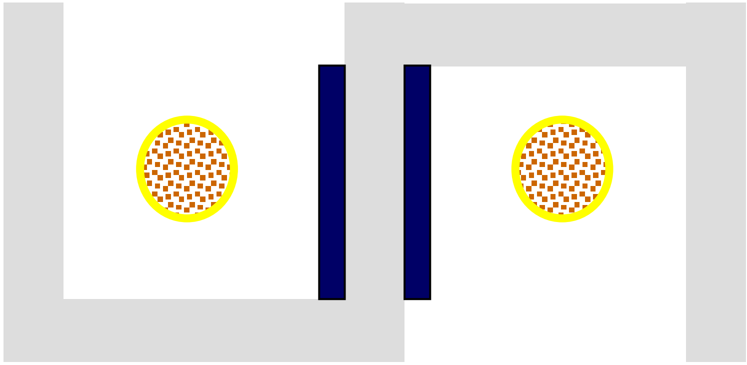


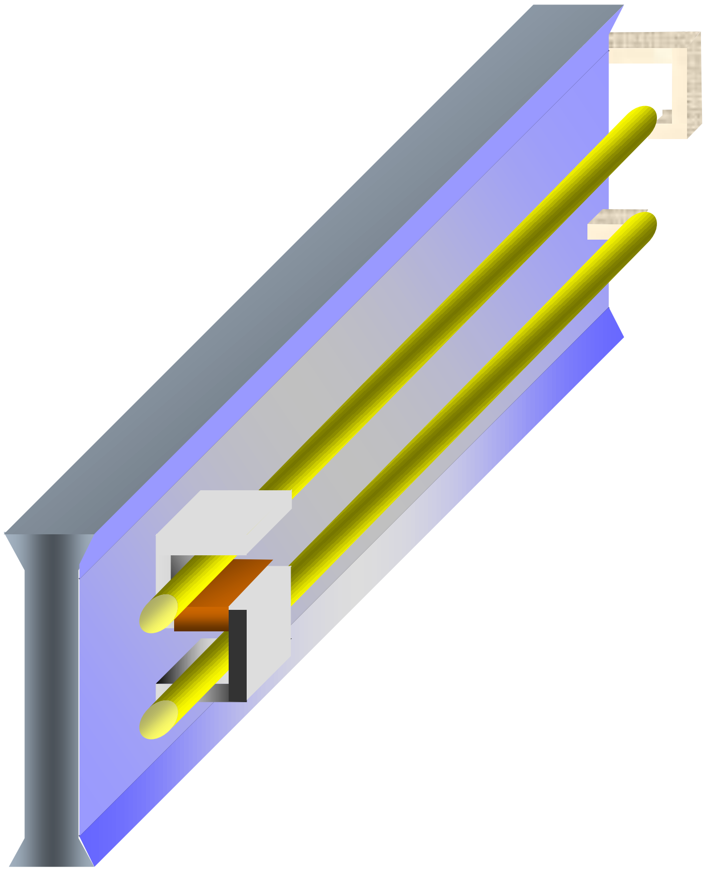
Solution: remove the flux cancellation path

Reference [17]

Pickup design: S Core

no cancelation path but more difficult to use

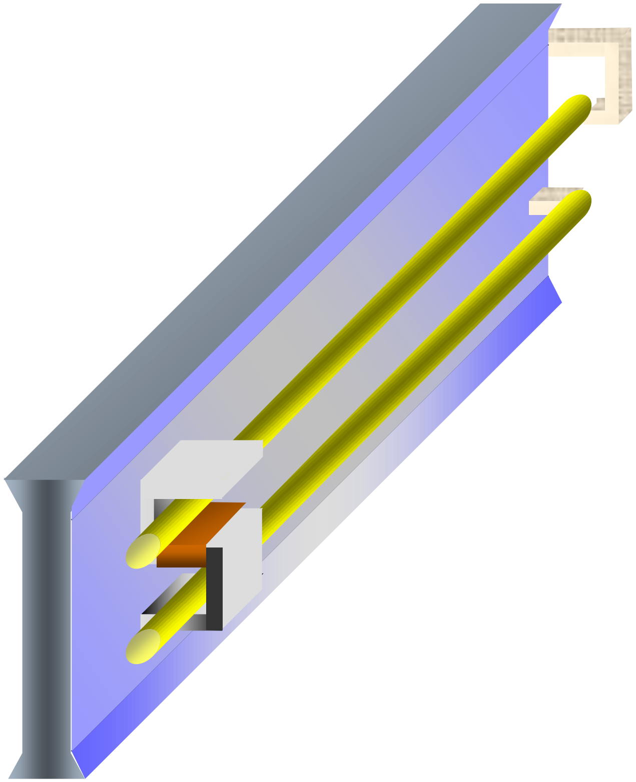




S-pickup on ICPT track

FEM Analysis:

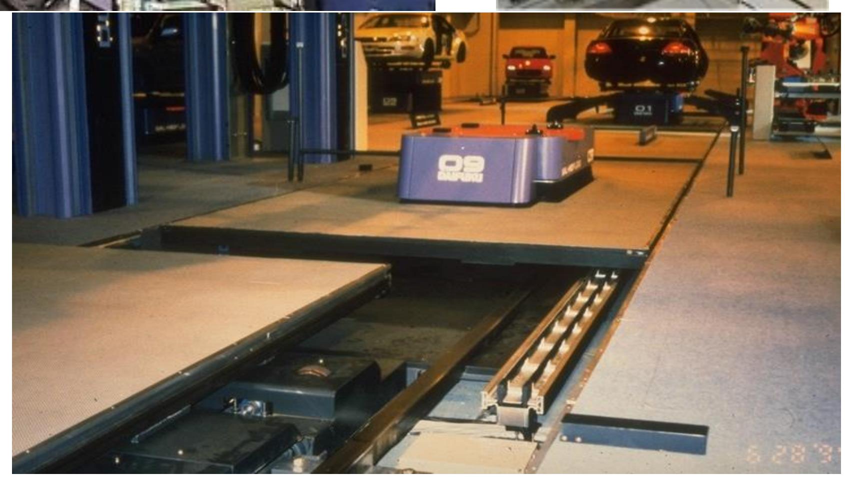
	S Core	E Core
V_{oc} (rms)	35.7 V	20.1 V
I_{sc} (rms)	4.4 A	4.0 A
S_u	158.5 VA	80.8 VA



- Uncompensated power comparison
- Identical material usage
- Complex assembly

Reference [17]

Factory Automation

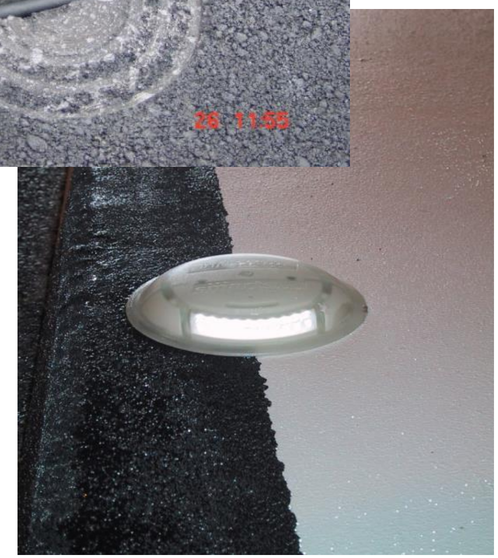


Daifuku: Materials Handling

Electronic Factory Automation

Daifuku: Clean Room Systems

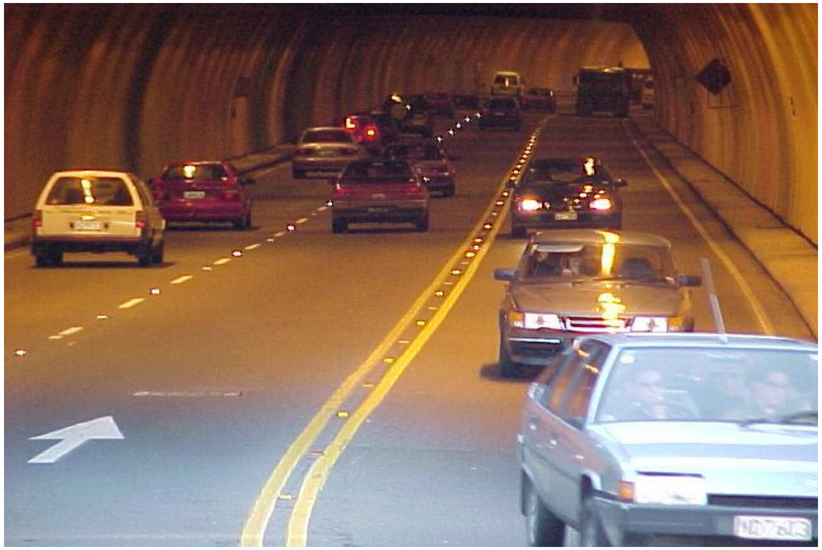
Traffic Control & Lighting:



Installation:

- Saw cut (10mm x 60mm)
- backfill epoxy/bitumen
- Glue stud into recess
- Active node/spacer placed beneath

Roadway Lighting



Tunnel (Wellington NZ)

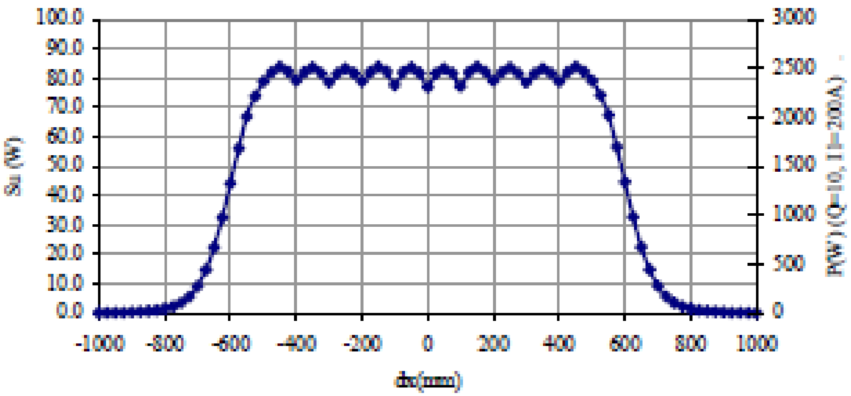
Tunnel (Sydney Australia)

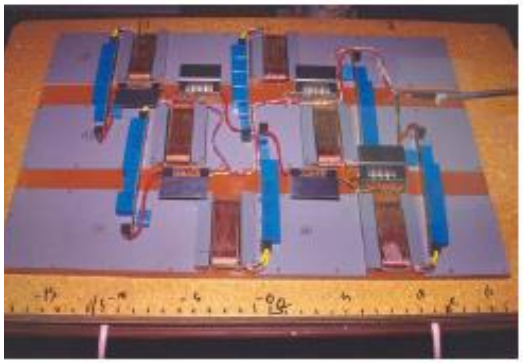
Double left turn (Illinois USA)

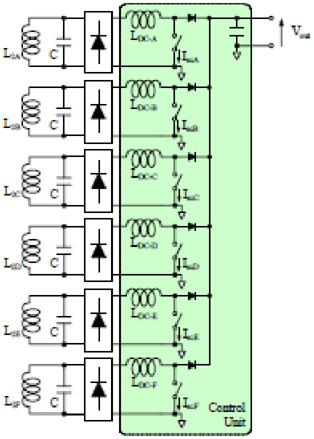
Amusement Rides

- Disney project
- Single phase track
- Multiple Pickups
- Wide tolerance

1994 Disney Imagineering







Automotive Materials Handling

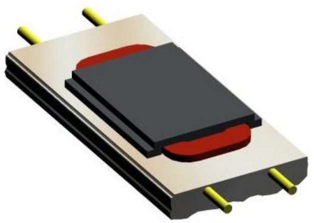
Conductix-Wampfler: IPT Track

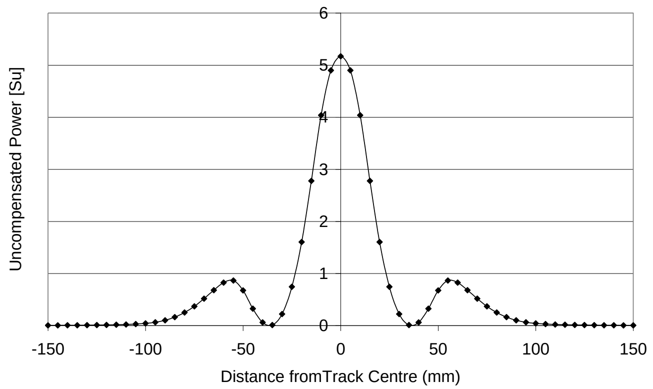
ACHIEVING GREATER FREEDOM

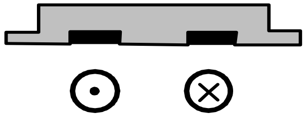
AGV Systems Early 2000s

- Redesigns to enable freedom of movement (Tolerance)
- Multiphase track options
- Multiphase Secondary options in a single secondary

AGV's and Robots

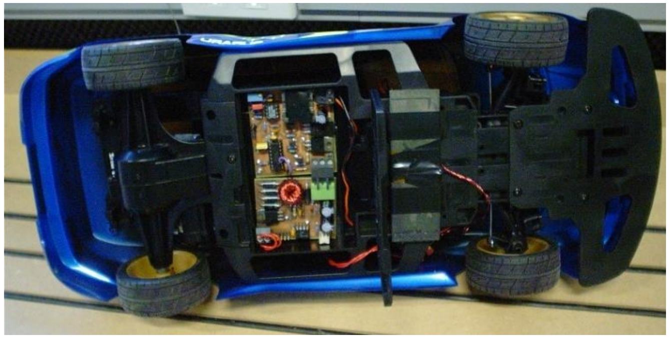






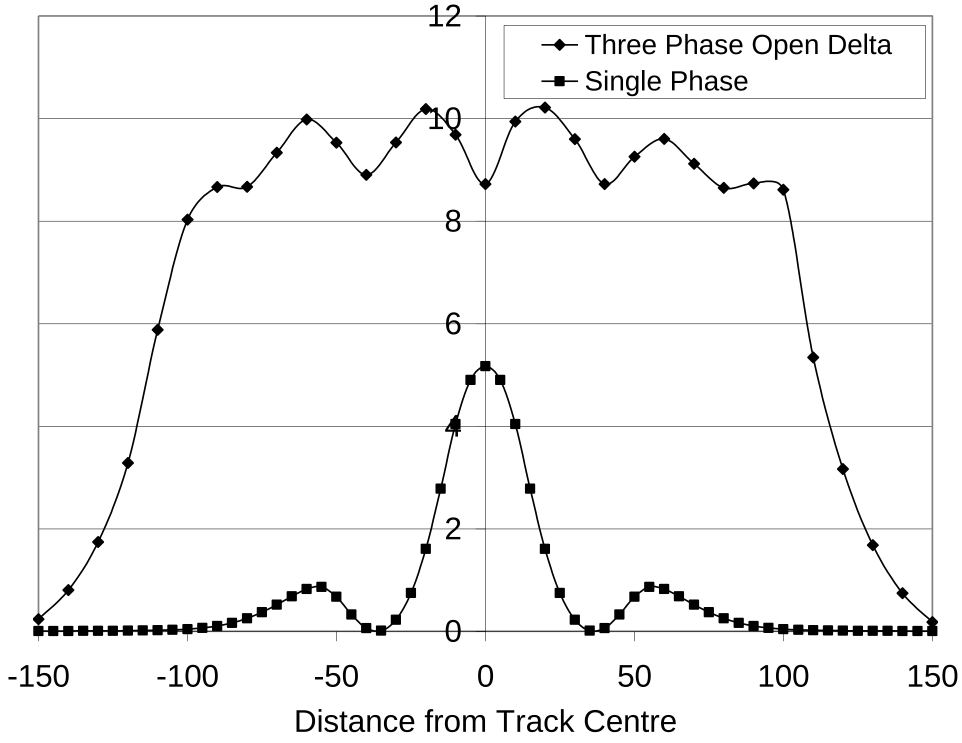
Precision alignment required for power transfer

Multi-phase tracks



Three phase tracks

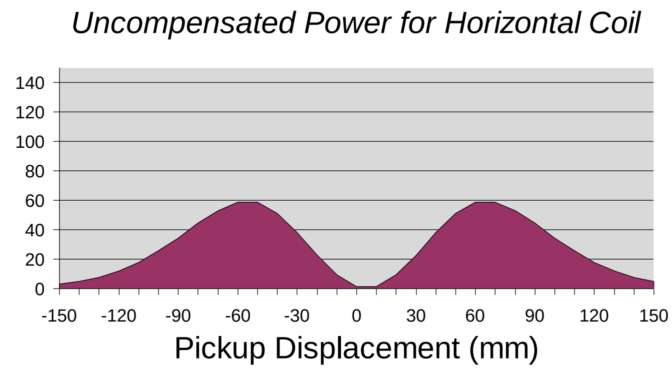
Multiphase systems

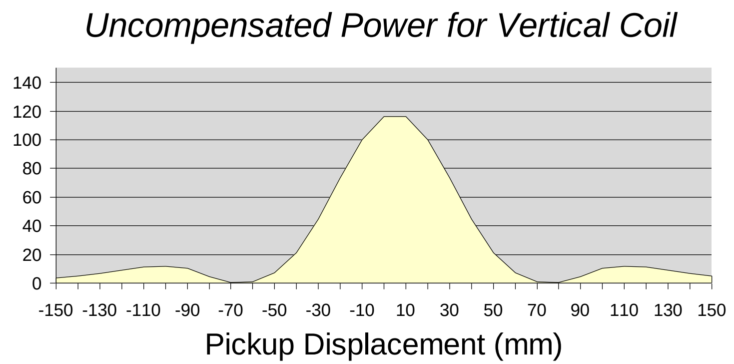


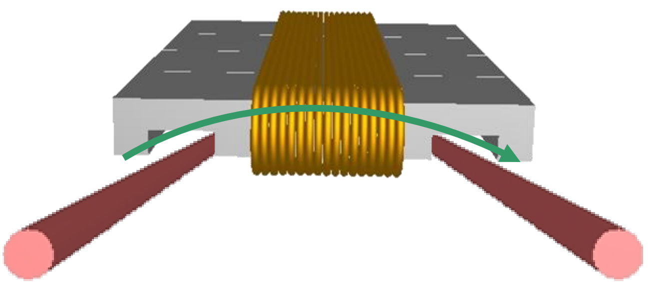
- New 3-phase design provides:
  - Excellent lateral tolerance
  - Higher power

Reference [18]

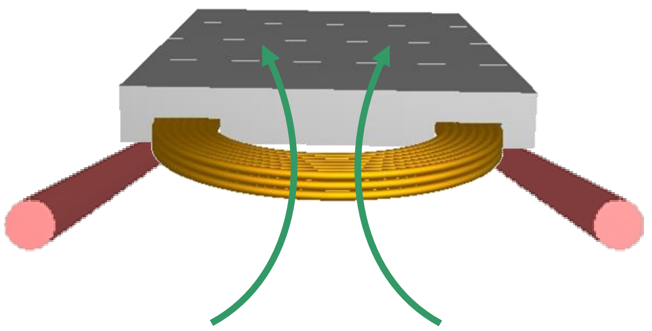
Independent Multi-coil Pick-ups





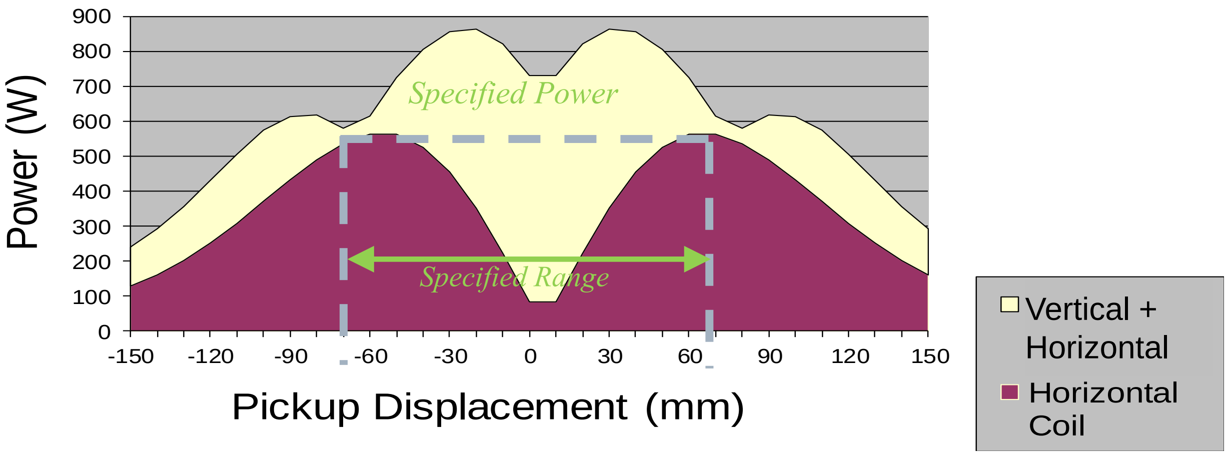


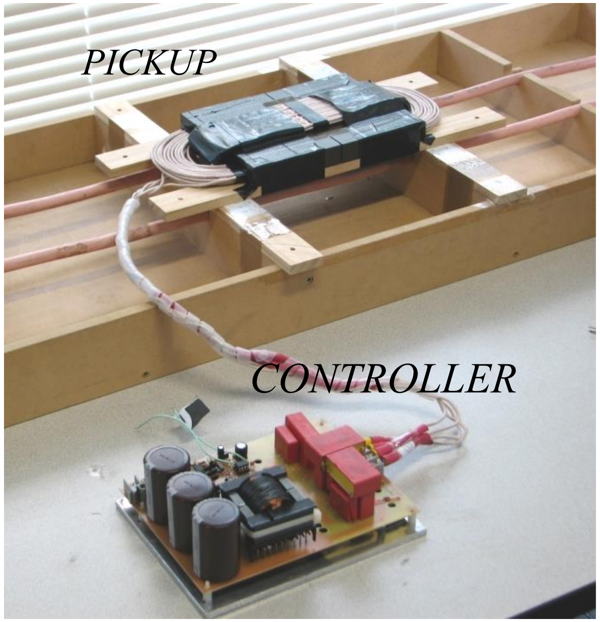
HORIZONTAL FLUX



VERTICAL FLUX

Independent Multi-coil Pick-ups

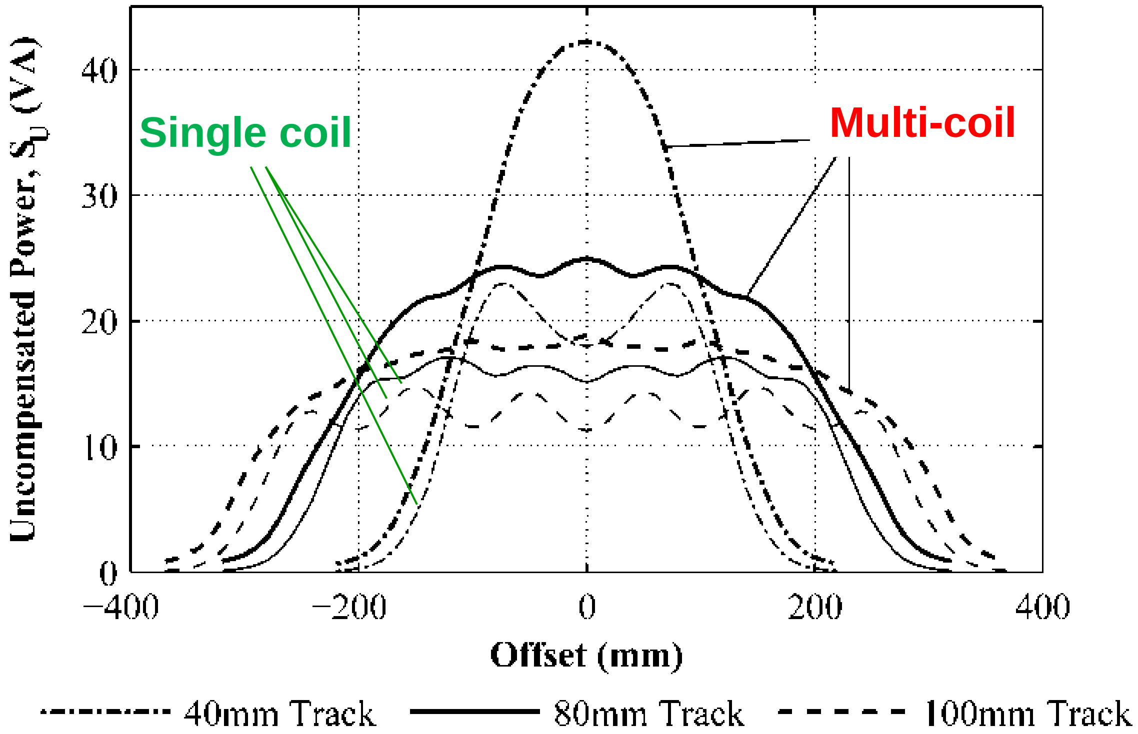




Adds significant lateral tolerance

Reference [19]-[20]

Multiphase Tracks and Multi-coil Pads



- Combined multi-coil
  - Flatter power profile
  - 25-50% more power

Reference [19]

DEVELOPMENT OF LUMPED CHARGING APPLICATIONS

References [2],[3],[7],[8],[9]

People Moving (Mid-late 1990s)

Whakarewarewa Rotorua Charging Bay


ipeNz

Arthur Mead Memorial Environmental Merit Award

Presented to

Wampfler Ag

for the application of environmental awareness to the solution of an engineering problem

People Mover at Maori Arts and Crafts Institute, Rotorua

Chairman

Secretary

June 1999

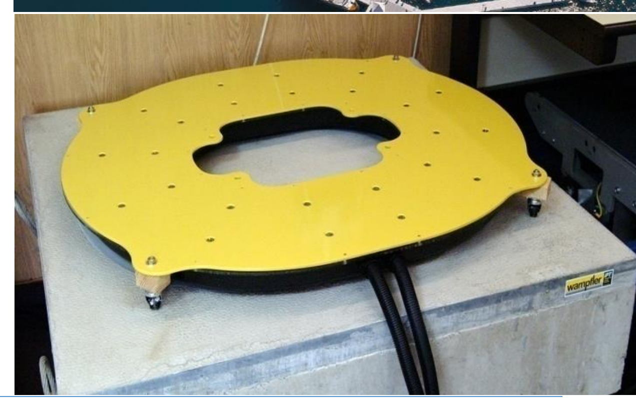
Date

- 5 buses with trailer
- 3 x 10 batteries of 12 V
- Charging: 7min /15-20 min
- Charging power: 20 kW

Conductix-Wampfler: 20kW Charging stations

People moving (early 2000s)

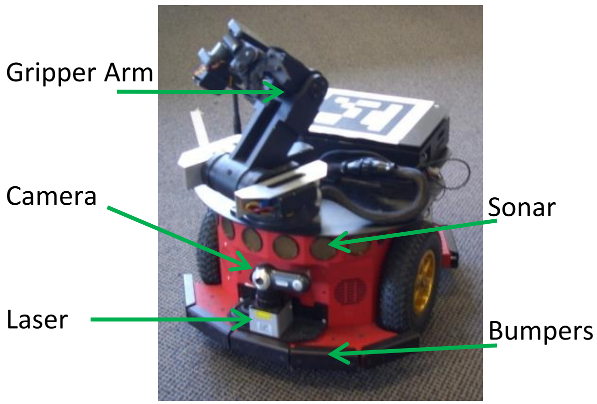
Genoa, Porto Antico



- 3 buses each with 56 x 6V Batteries
- Charging 60kW for 10 minutes/hour

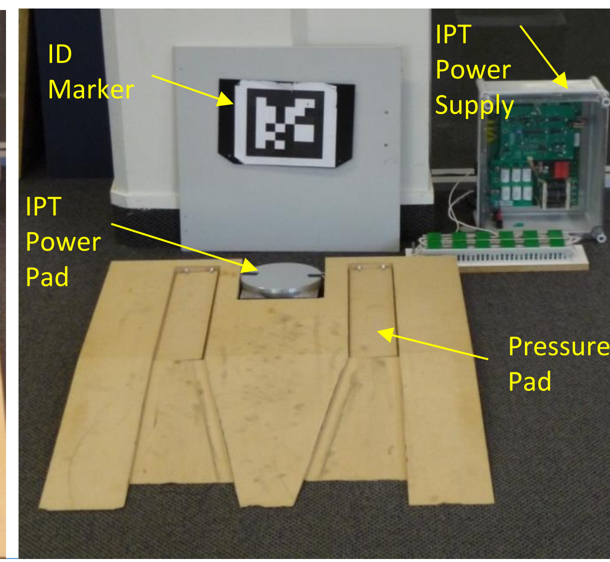
Conductix-Wampfler: 30kW Charging Pick-ups

50W Robotic Charging



Wireless Charging as required

ID marker identifies charger position



200W Shopping Basket Chargers

Charging Station

Power pad sited under trolley

Charging Mat in Walmart USA

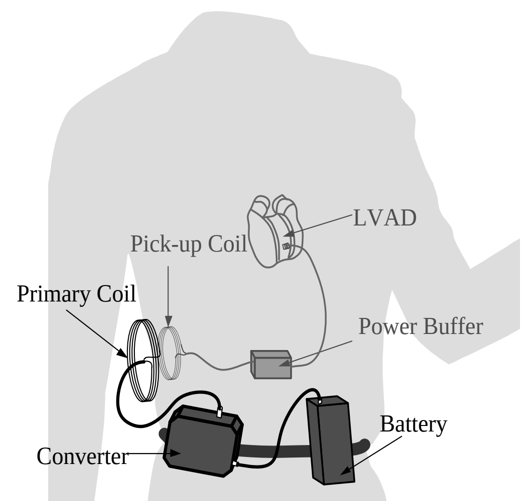
IPT powered shopping baskets

Low Power Applications

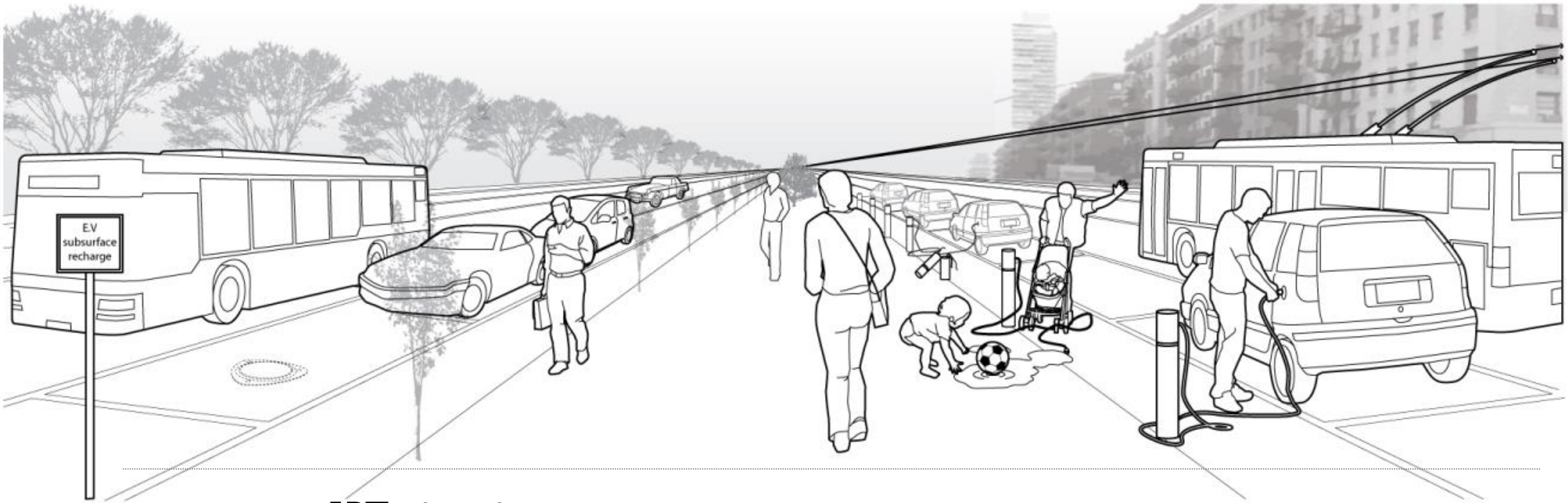




- Millar research
  - Heart pumps
  - Biomedical sensors
- Power by Proxi
  - Home applications
  - Inductive Slip-rings



A New Vision mid 2000s



IPT street

Conductive charge street

Safe and Durable

Easy to use

Aesthetically pleasing

CHARGING PADS FOR ELECTRIC VEHICLES

Design Metrics

- Secondary: robust, thin and light
- Primary: Robust is critical
- Cost effective & efficient
- Excellent coupling with low leakage
  - meets ICNIRP
- Scalable for cars, trucks or buses
  - Ground clearance is vehicle dependent and varies with suspension, loading …
  - Horizontal tolerance aids unassisted parking

Operating Methodologies

- Power output: $P_{out} = V_1 I_1 k^2 Q_2$
  - V_1 regulated for safety
  - I_1 increases power (but also losses)
- Operating Q of the primary (ground) pad $Q_1 = VA_1/P$
- Operating Q of the secondary (vehicle pad) $Q_2 \approx VA_2/P$
- Losses in any pad as function of Pad quality $P_{loss} = \frac{VA_{Pad}}{Q_{L_{Pad}}}$
- Control Options
  - Primary side control only: Only Q_1 varied
  - Secondary side control only: Only Q_2 varied
  - Primary & secondary side control: Achieves lowest loss. Both Q_1 and Q_2 varied.

Coupling Variations

- Typical coupling factor: $0.1 < k < 0.4$
  - Impacted by height variation
  - Impacted by relative alignment
  - Desirable range 0.1-0.25

$$\zeta_{max} \cong \frac{1}{1 + \frac{2}{k\sqrt{Q_{L_1} Q_{L_2}}}}$$

- Typical pad quality factors $Q_L \approx$ 500-700

- Power impacted by k^2

$$P_{out} = V_1 I_1 k^2 Q_2$$

  - If $k^2 = 0.1$ the VA in the primary or secondary (or a combination) must be 10x greater than P_o
  - If $k^2 = 0.01$ the VA in the primary or secondary (or a combination) must be 100x greater than P_o

Effect of Coupling

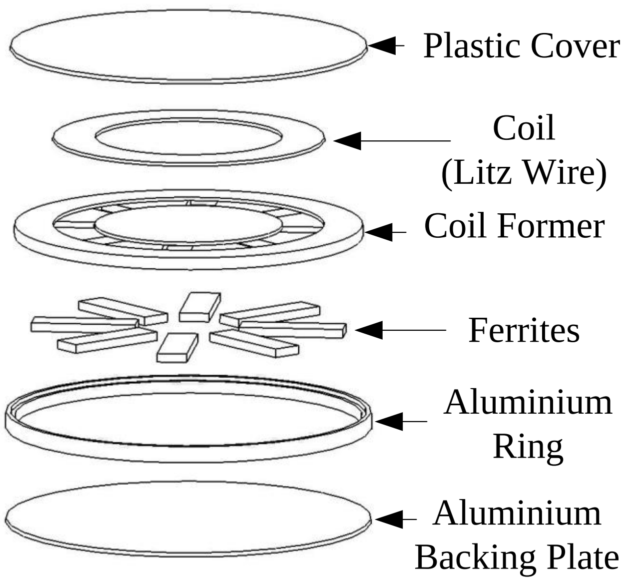
Pout	k	k^2	VA_1	Q_1	Q_2	VA_2
3.3kW	0.316	0.10	33kVA	10	1	~3.3kVA
3.3kW	0.316	0.10	10KVA	3.16	3.16	~10kVA
3.3kW	0.316	0.10	3.3kVA	1	10	~33kVA
3.3kW	0.10	0.01	330KVA	100	1	~3.3KVA
3.3kW	0.10	0.01	100KVA	31.6	3.16	~10kVA
3.3kW	0.10	0.01	33KVA	10	10	~33kVA

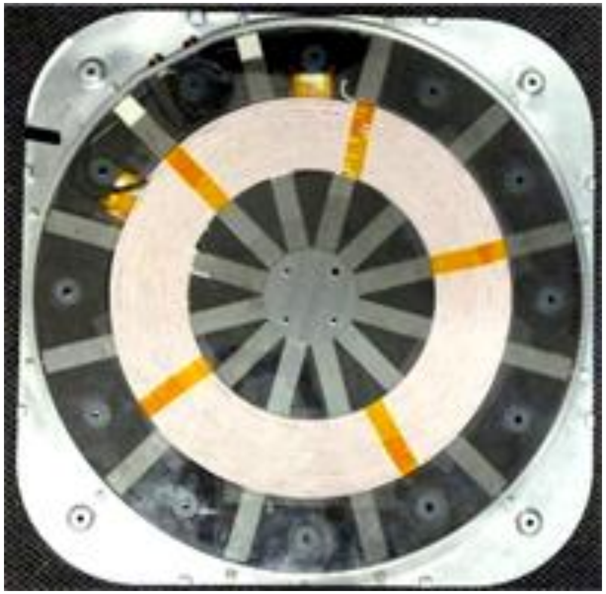
Magnetic loss concepts (assume pads with similar Q_L ~500)

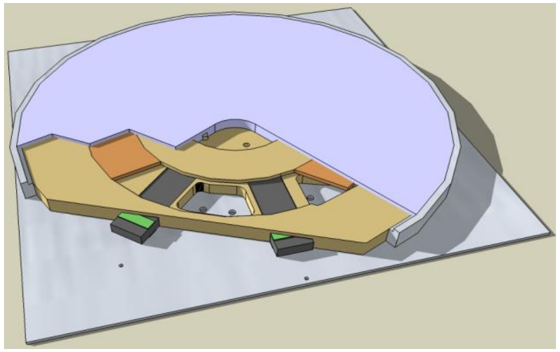
$Q_{L_{1,2}}$	k^2	Q_1	**~ Loss in primary pad**	Q_2	**~ Loss in Secondary pad**	**Total Pad Losses**
500	0.10	10	2%	1	0.2%	2.2%
500	0.10	3.16	0.63%	3.16	0.80%	1.4%
500	0.10	1	0.2%	10	2.5%	2.5%
500	0.01	100	20%	1	0.2%	20%
500	0.01	31.6	6.3%	3.16	0.63%	6.9%
500	0.01	10	2%	10	2 %	4%

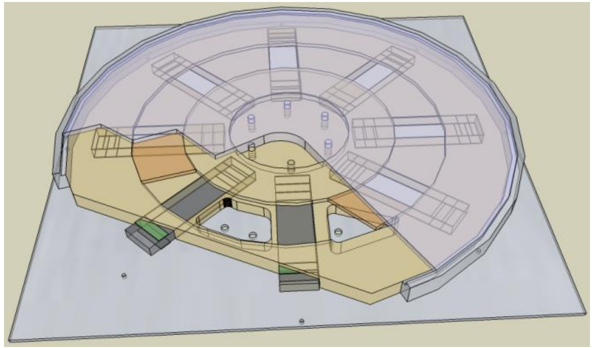
NON-POLARISED COUPLERS

Circular Pad



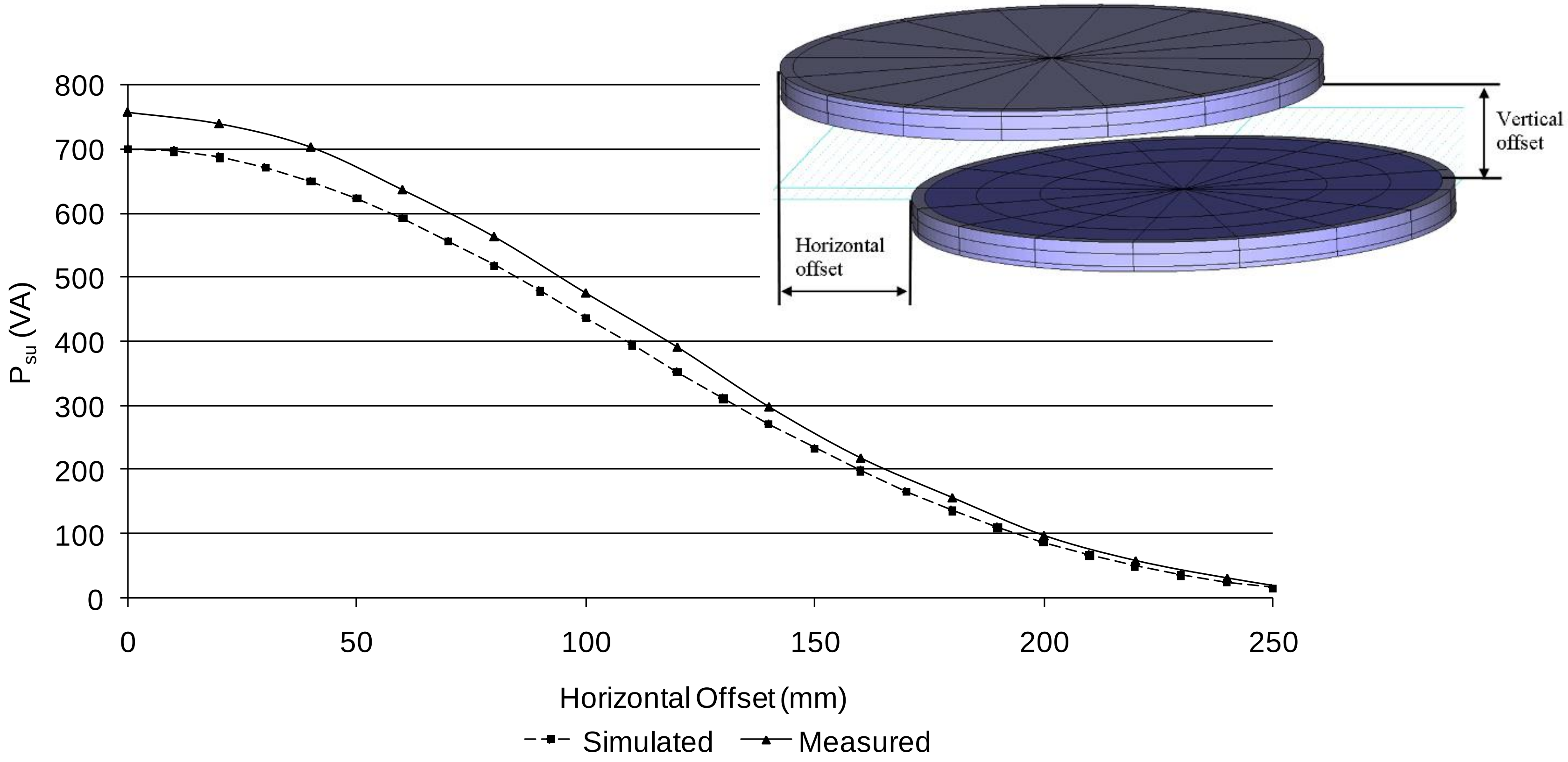






High Q_L (~ 300 at 20kHz)

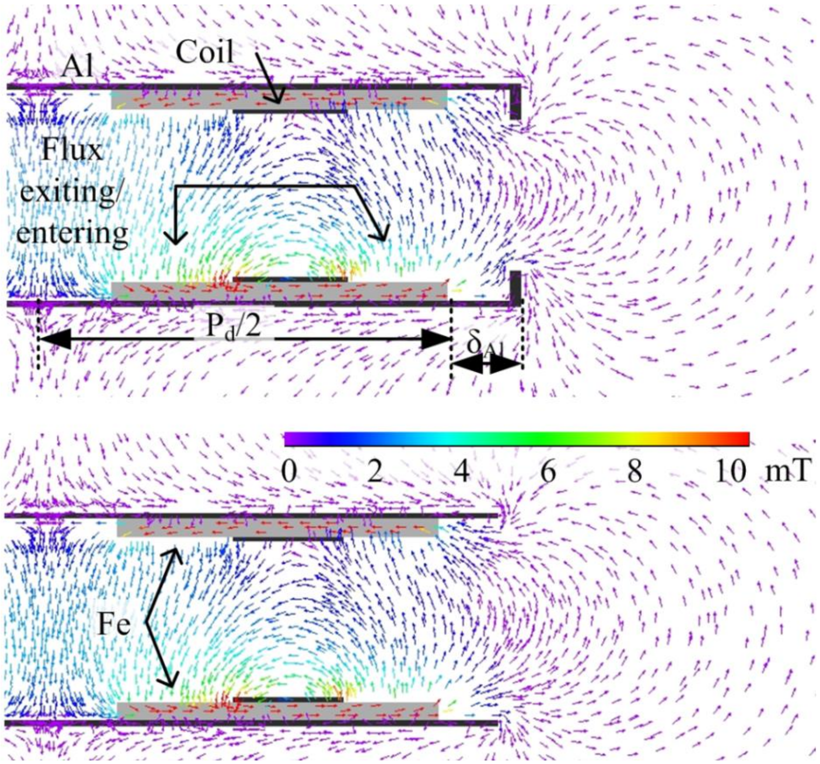
Performance of Circular Pad

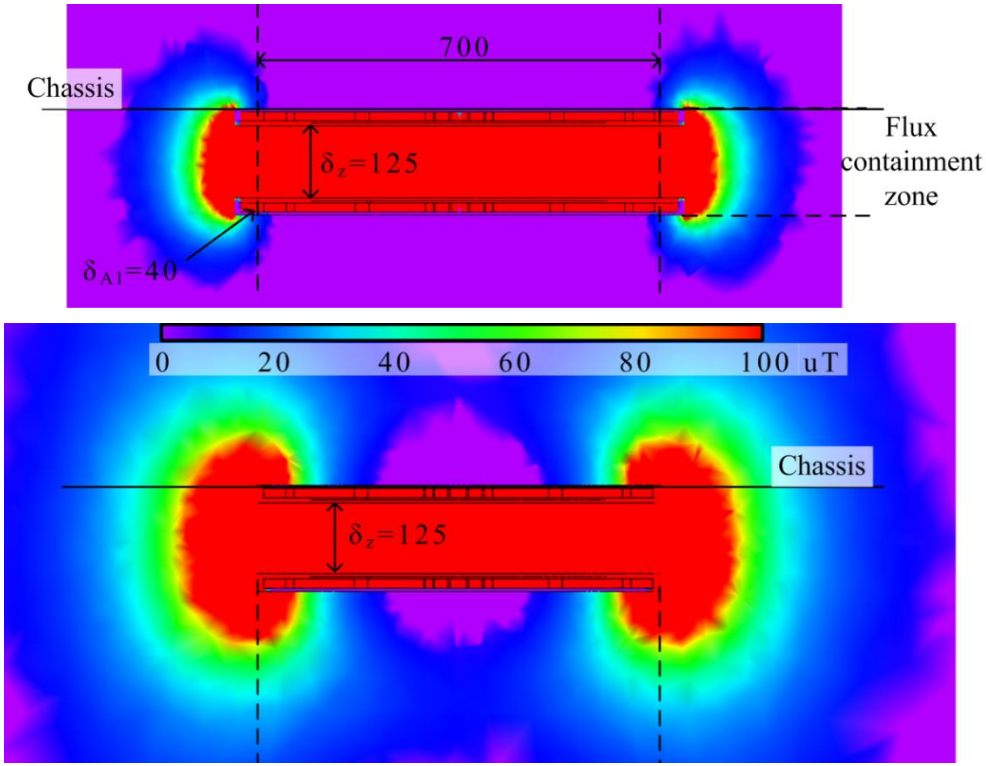


Performance at 210mm Vertical offset and increasing Horizontal offset

P_{out} =2kW, Horizontal o/s limit Q=6: ~ 130mm

Circular Coupler Shielding





- Installation - EV chassis modification

A Demonstration System

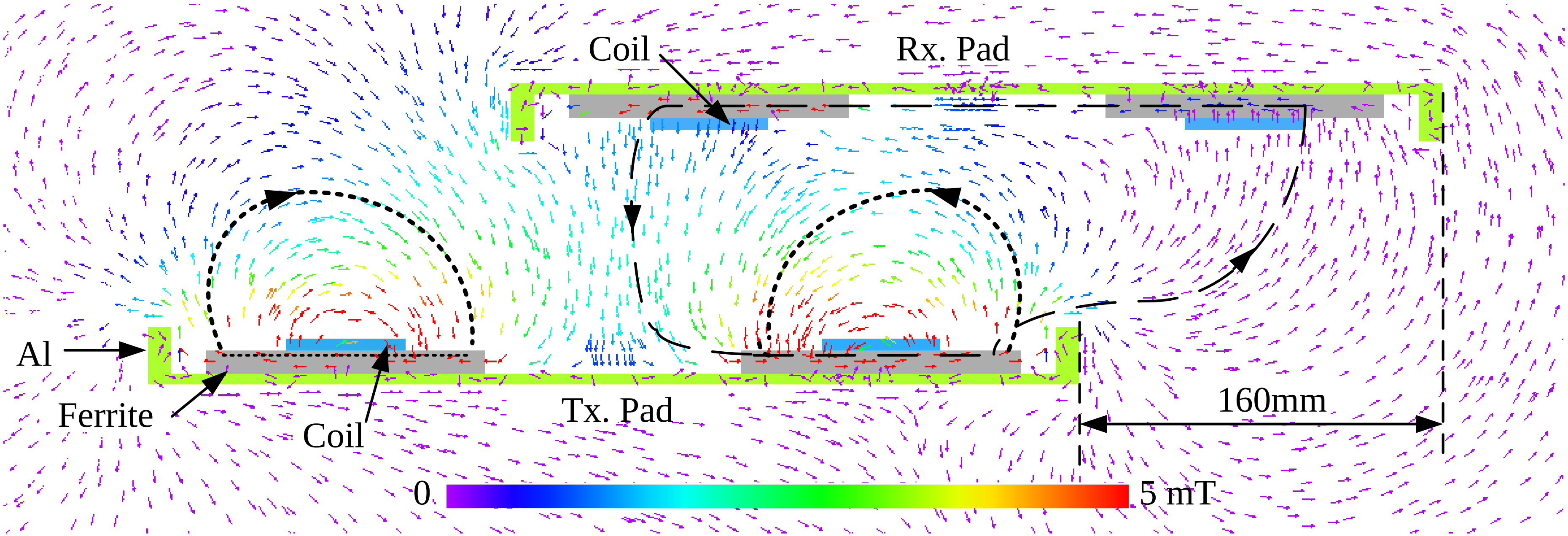
Vehicle controller

Charger: 2kW single phase supply

220mm airgap

2kW IPT Charger at EVS24

Circular Coupler Limitation

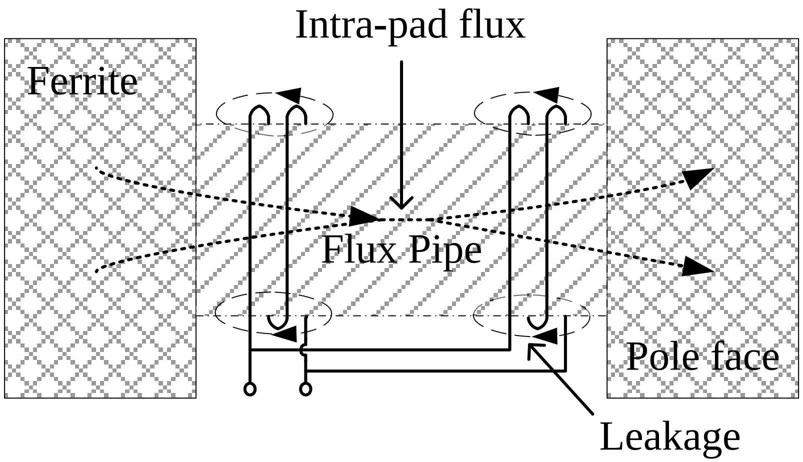


- Power null in all directions (around 40% pad diameter)
- Limited to Stationary Applications

POLARISED COUPLERS

Reference [8],[22]

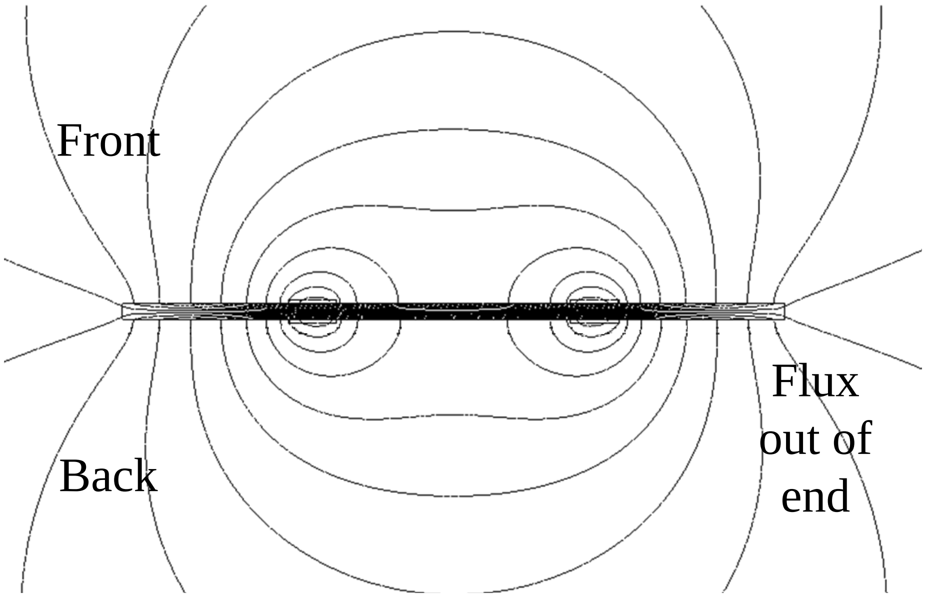
Polarized Designs: Solenoid

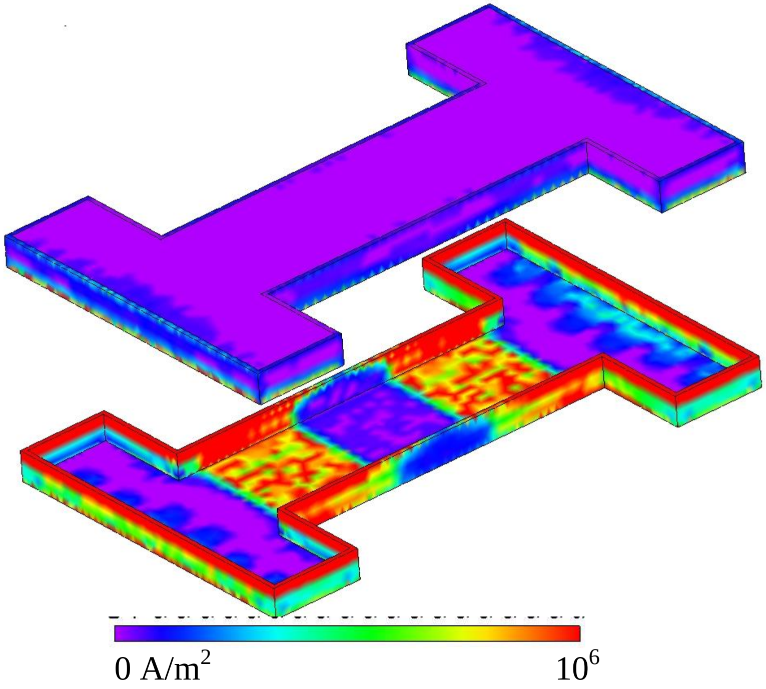


Flux pipe:

- encourages pole separation
- flux path has greater height

Solenoid Coupler





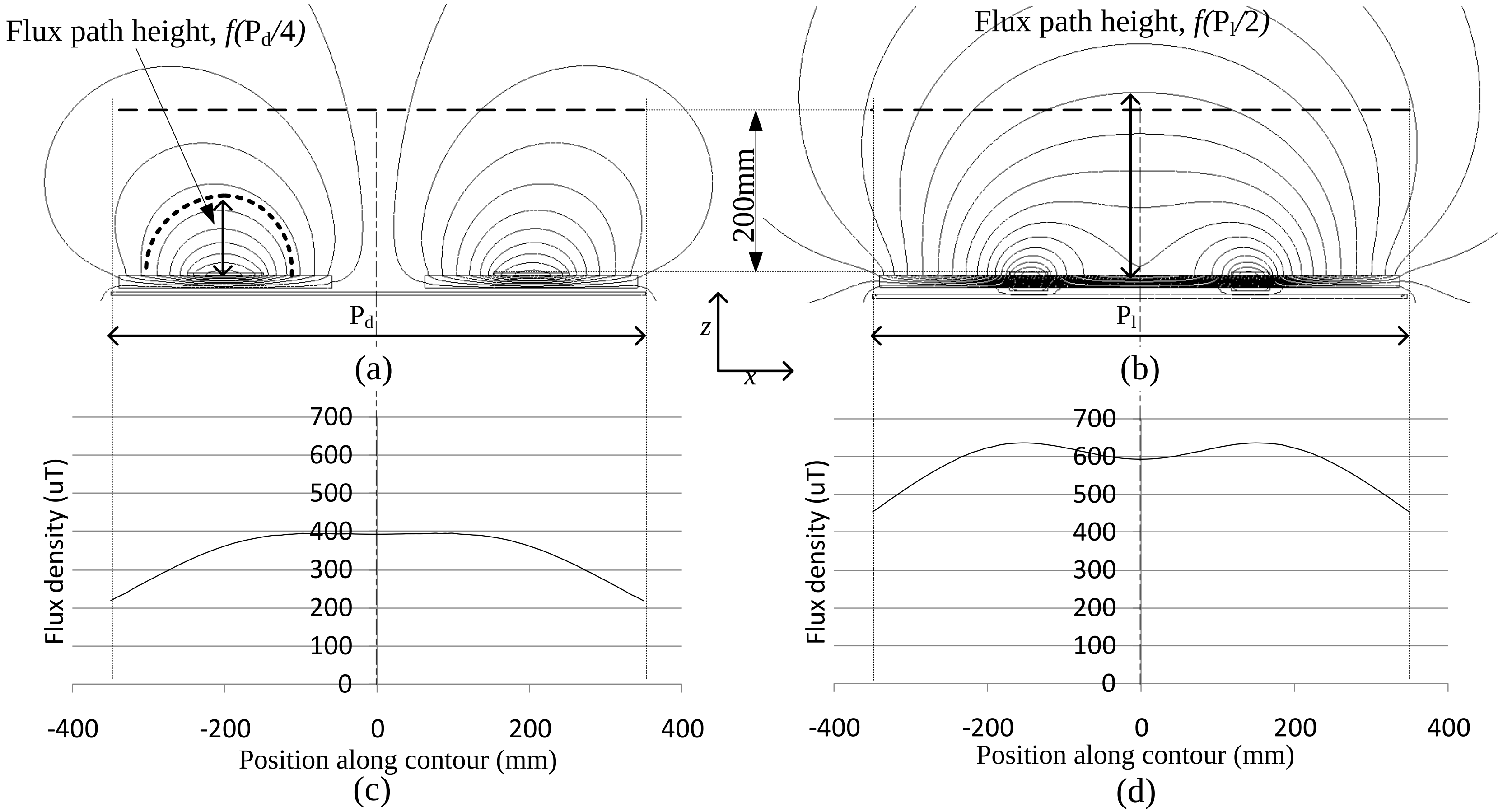
Shielding with aluminium creates large losses

I_1 = 23A/coil at 20kHz

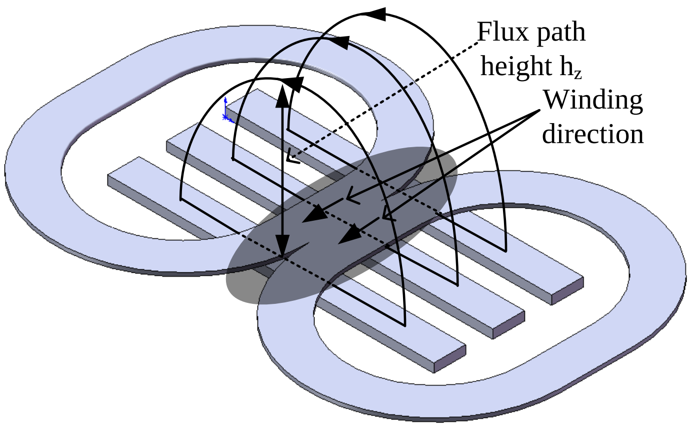
- Q_L without shielding is 260
- Q_L with shielding is 86

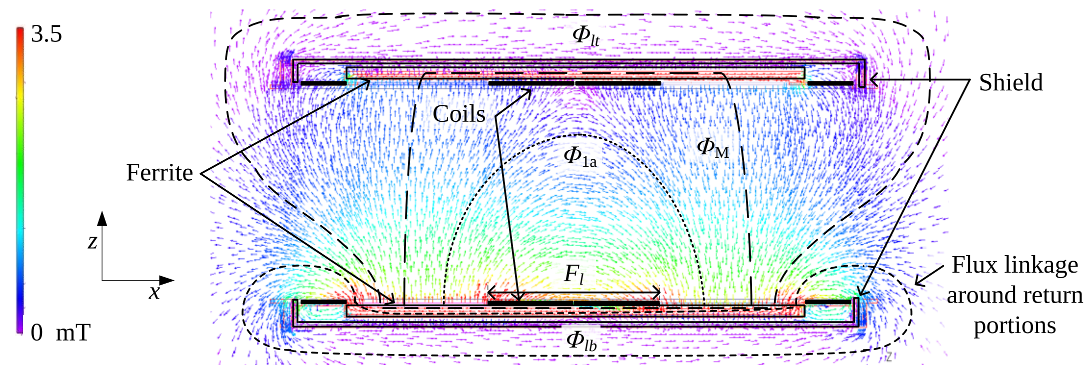
$$Pad_{Losses} \propto \left(Q/Q_L\right)$$

Improving Coupling



Polarized DD & Single Sided Fields





Ferrite strips:

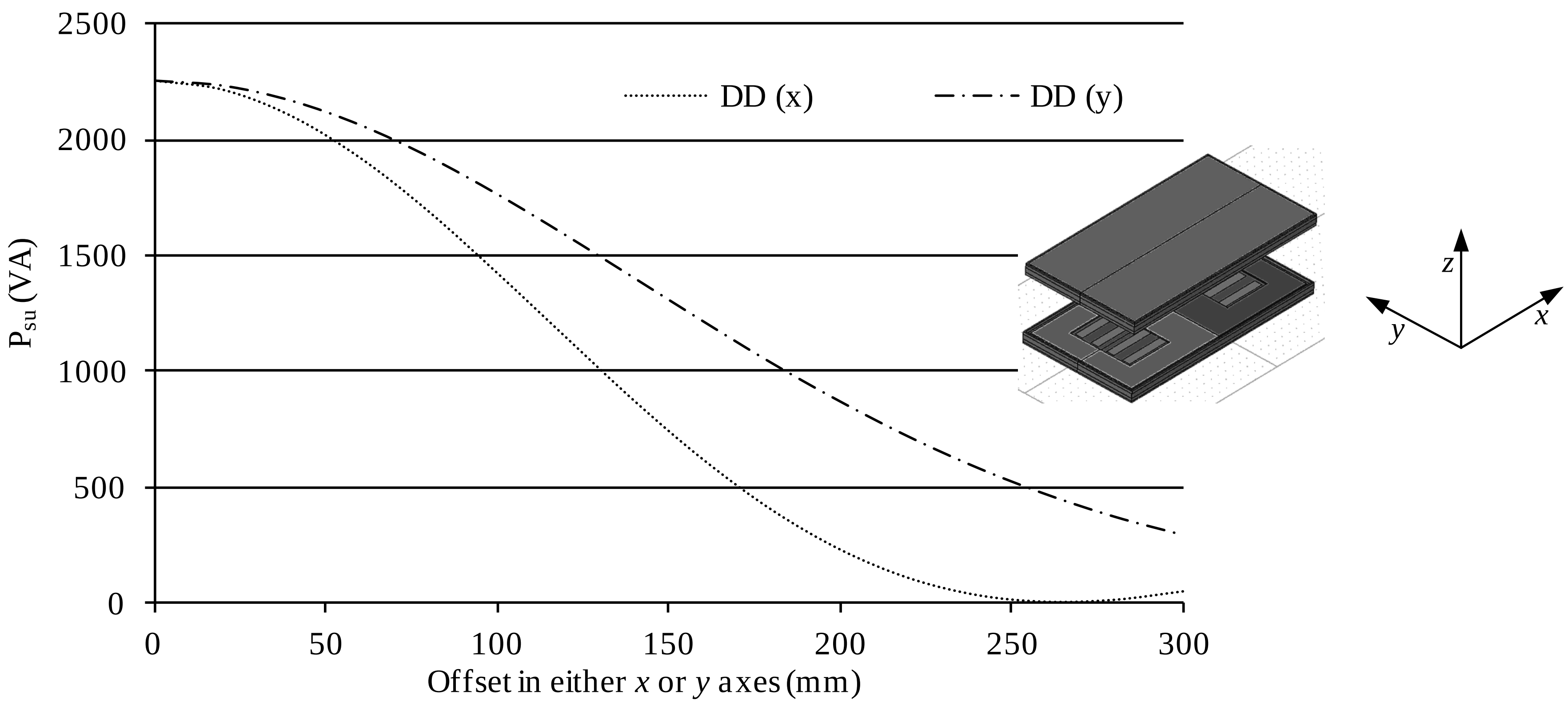
- Reduce material and inductance

Coil winding:

- Creates a flux pipe (minimised winding length)
- Has single sided flux paths with height ~ *pole seperation* /2

Has Q_L ~400 at 20kHz
Single Sided polarized flux paths

Polarised DD



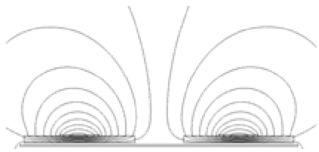
Performance with lateral offset

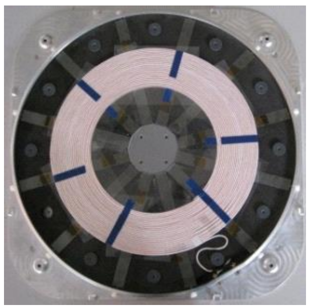
Performance Comparisons

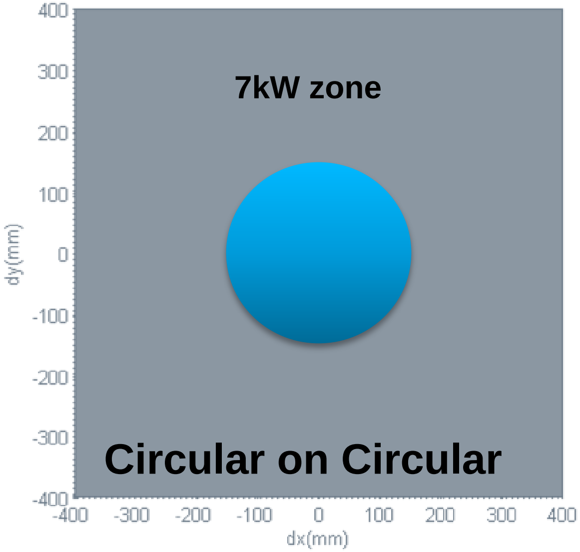
- Similar Areas and Inductances of Pads
- Similar Driving VA and Frequency
- Similar Secondary VA
- 7kW output at 125mm

Non-polarized vs. Polarized

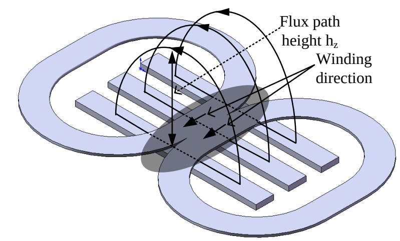
Transfer height d/4

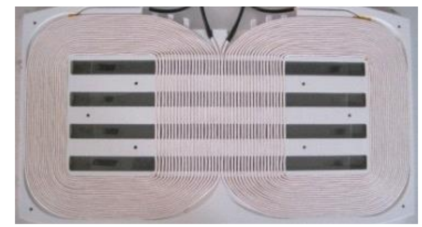


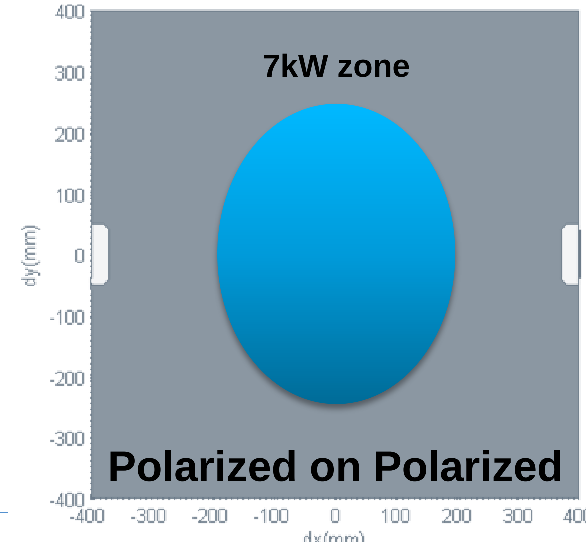




Transfer height d/2







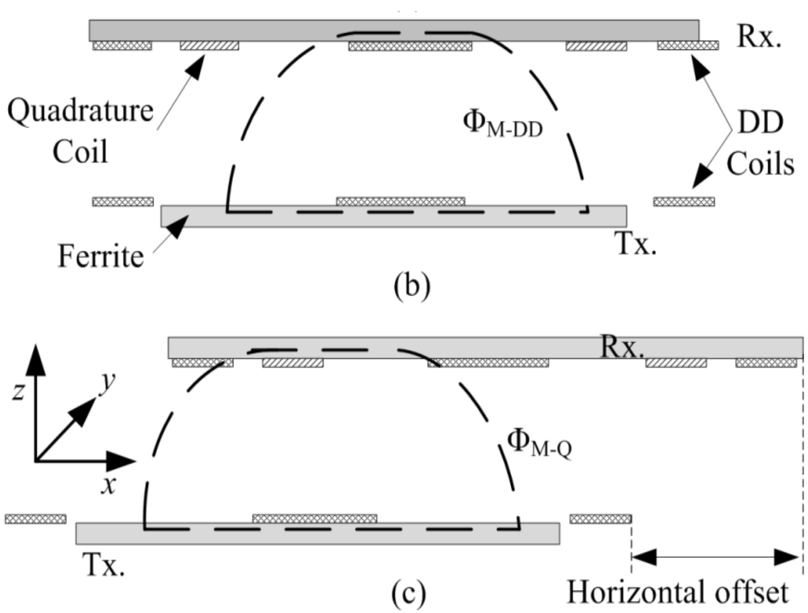
Charging Area

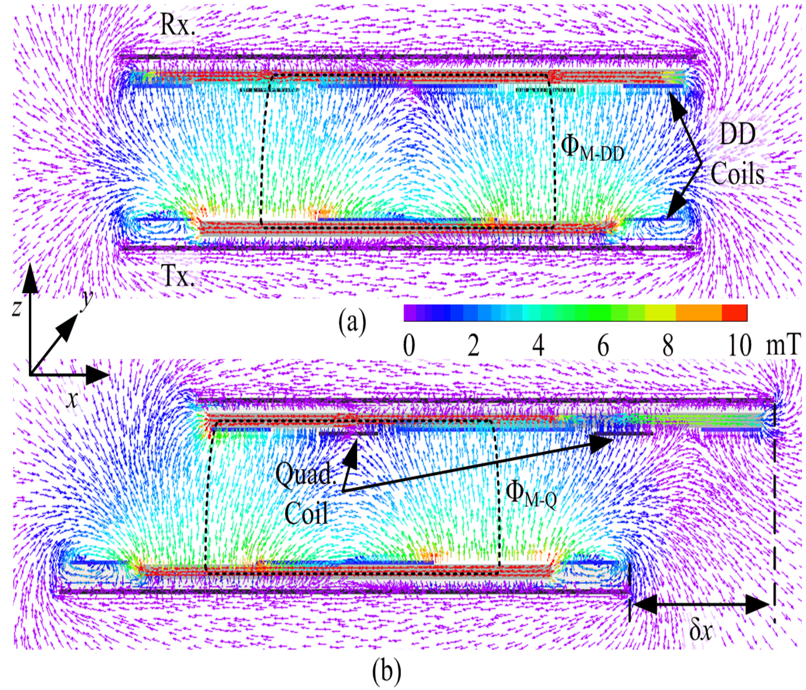
Circular < 2x Polarised

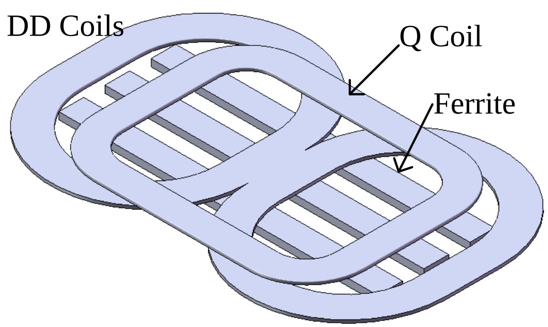
MULTICOIL COUPLERS

References [22]-[23]

Multi-coil DDQ Secondary



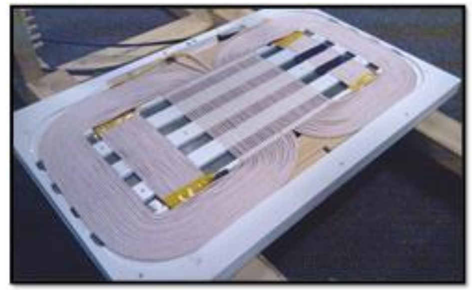




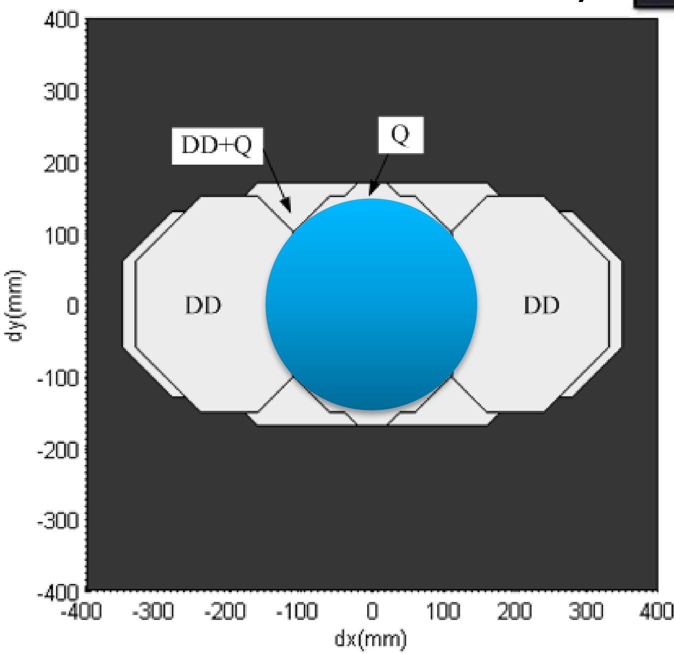
A second coil added to DD

- Spatial quadrature coil
- Improves lateral tolerance

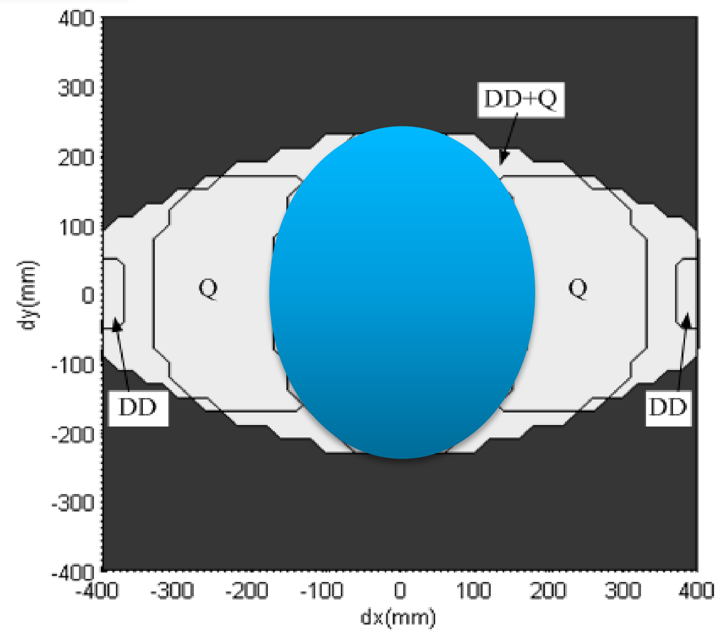
Multi-coil on Various Primaries



Non-Polarized Primary

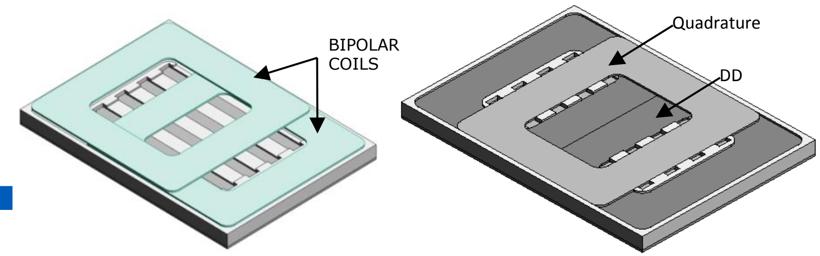


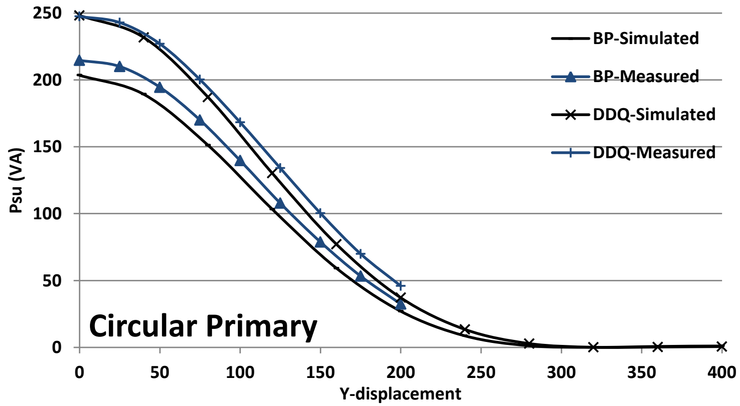
Polarised Primary

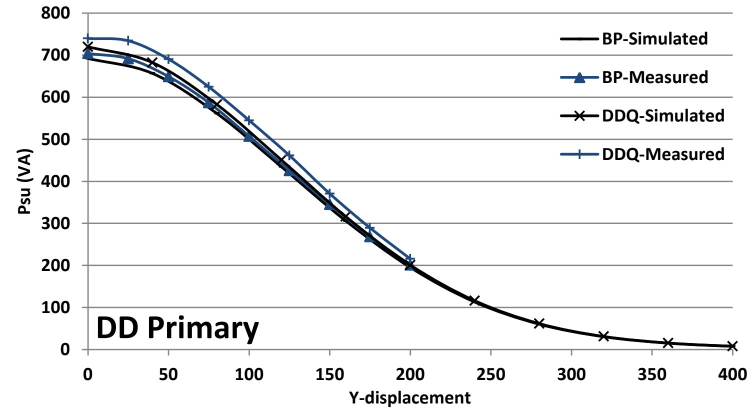


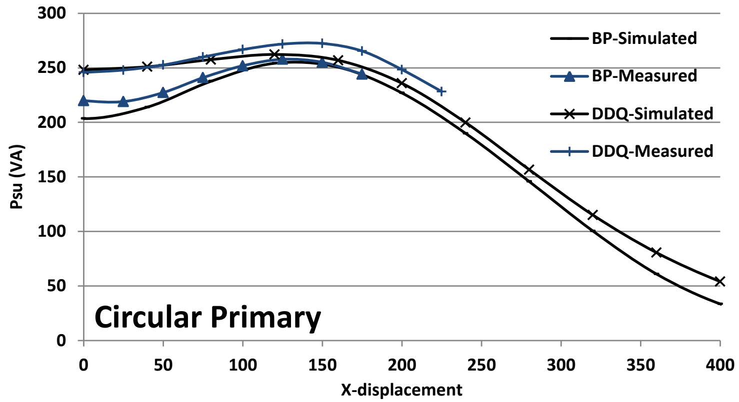
Charging area 3 x greater

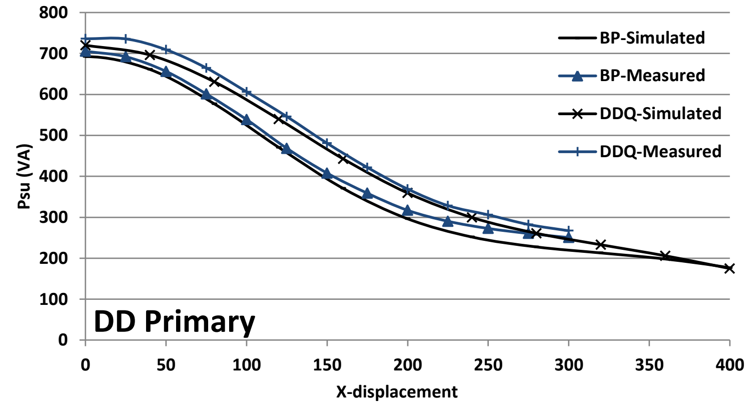
Bipolar Option





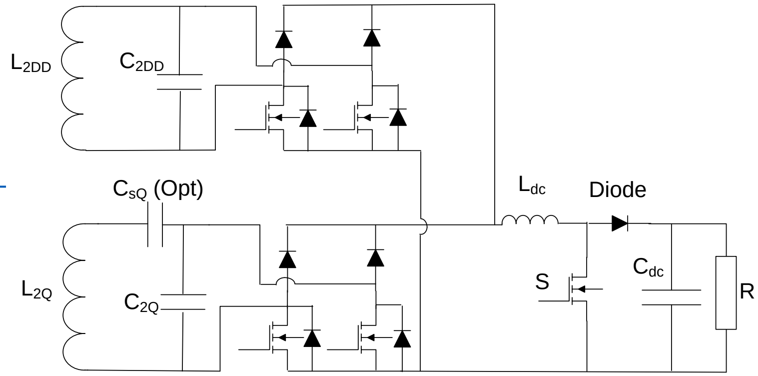






- Independent coils with 25-30% less copper
- Power transfer < 10% difference

Multi-coil Controllers



Secondary side coils are independent:

- High coil quality factors (Q_L)
- Packaged within the same magnetic design
- Have independent coupling coefficients (k) which
  - vary with position
  - complement each other

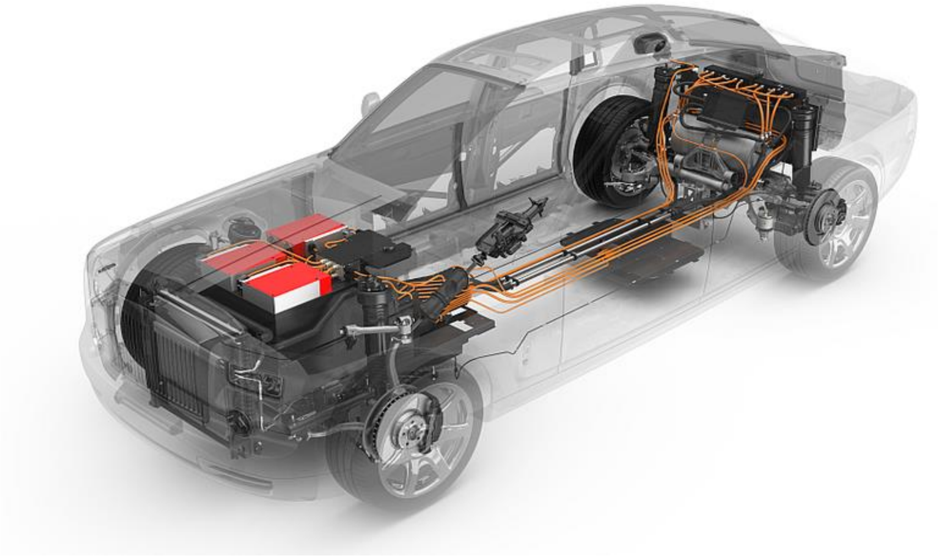
The operational Q can be kept low

- Use either or both coils if k is high
- Can reduce losses by turning off a coil if its k is low

HaloIPT Evaluations

Rolls Royce Phantom 102Ex with HaloIPT wireless charger

Affixed vehicle pad &
Transmitter pad



3.5kW & 7.5kW Chargers >90%

The Future:Dynamic Highway Power

Allows lower battery weight but Gaps 20-40cm

Conclusions

- WPT Development
  - Imagined 1890s, and showcased
  - Rediscovered in mid-late 90s
  - Commercially practical late 90s in niche markets
  - Impacting our home market today
- Opportunities & Challenges
  - Broad set of applications
  - Costs are reducing but need to be lower
  - Robust design while meeting emission restrictions
  - EV solutions are already being adopted
- Roadway powered EV’s are part of the future
  - Challenge is to make them robust & economic

Questions?

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