On-Line Electric Vehicle (OLEV) Project and Vehicular Wireless Power Transfer Technology

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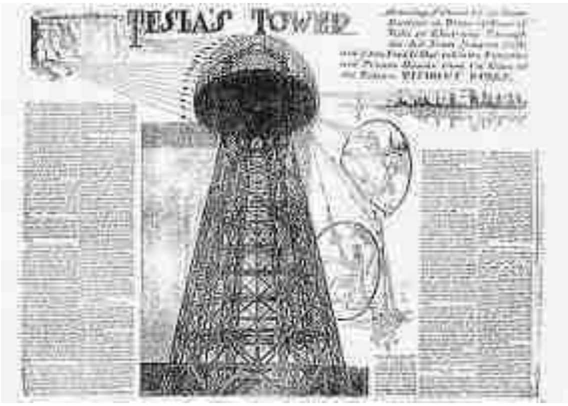
Contents

Wireless Power Transfer Technologies

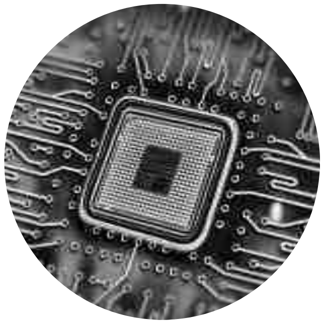
- **Nikola Tesla** (New York American, May 22, 1904)
  - Tesla's Tower [1]
    - Scheme of drawing millions of volts of electricity through the air
    - From Niagara Falls out to cities, factories and private houses from the towers without wires.



- **MIT** (Science, July, 2006)
  - Wireless Power Transfer via Strongly Coupled Magnetic Resonances [2]
    - Self-resonant coils in a strongly coupled regime
    - Experimental demonstration of wireless power transfer
    - 60 watts with ~40% coil-to-coil efficiency over distances of 2 meters

Ref. : 1) http://www.teslasociety.com/tesla_tower.htm 2) http://www.witricity.com/pages/papers.html

Applications of Wireless Power Transfer Technology





IC / Package	Sensor / Medical	Mobile / Home	Automobile / Train / Robot	Space
mW	mW~W	W	kW~MW	~GW
mm	cm	cm	m	km

Size & Distance & Power

Categorization of Wireless Power Transfer Technologies

	Magnetic Resonant (Magnetic Induction / Resonance)	**Microwave**
Frequency	**kHz ~ MHz** (20, 60, 85 kHz for EV) (100~300 kHz, 6.78 MHz for Mobile)	**GHz** (2.45 GHz, 5.8 GHz)
Distance	**cm ~ m**	**m ~ km**
Power	**mW ~ MW** (mW~W for Sensor) (kW~MW for EV and Train)	**mW ~ GW** (mW for Sensor, IoT) (5~10 W for Mobile) (kW~MW for SPS*)
Efficiency	**50 % ~ 95 %**	**10 % ~ 70 %**
Application	**Mobile, EV**	**Mobile, Long Dist.**

***SPS: Solar Power Satellite**

Electric Vehicle – Necessity of Green Transportation

Exhaustion of Oil Resource

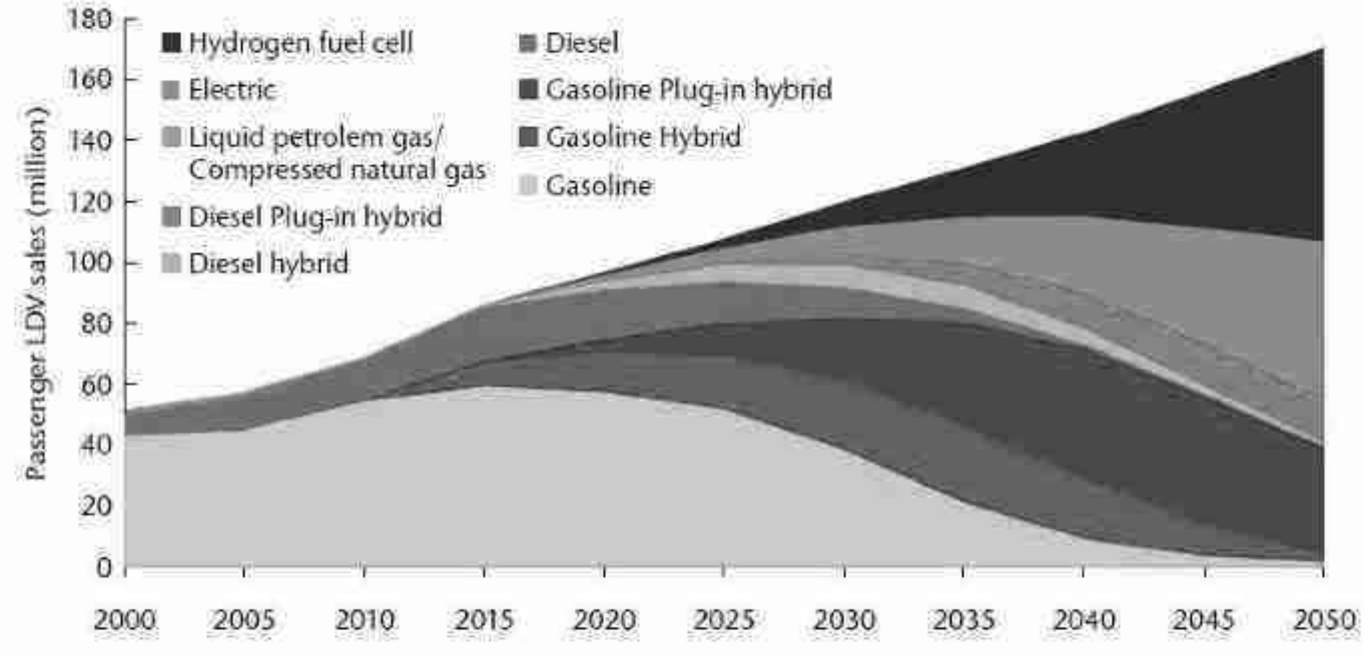
Environmental Pollution

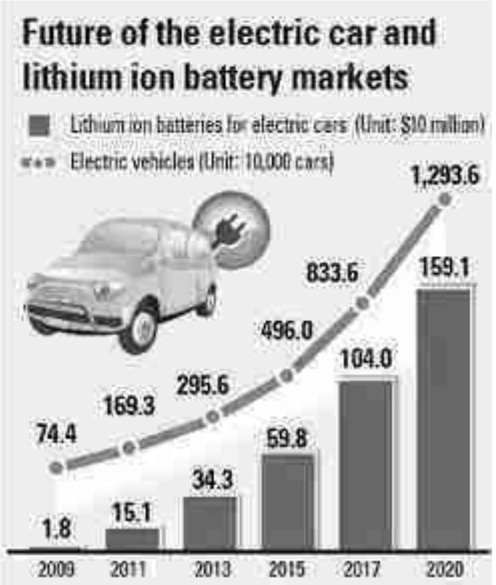
Air Pollution,
Energy consumption,
Traffic Accident,
Discomfort

Demand for eco-friendly, low-cost, and highly-efficient transportation system

Electric Vehicle – Battery Dependency

- The dependency of the battery in electric vehicles is increasing.





Source: International Energy Agency 2009 (http://www.iea.org)

Source: JP Morgan

Electric Vehicle – Problems in Battery

- Battery charging/changing time is still longer than fueling.
- Battery is the most expensive part in EV.

EV Battery Issues
(Weight, Price, Capacity)

Transmission 5%

Power Electronics 2%

Motor 15%

Electro-mechanic Devices 19%

Lithium Ion Battery 59%

EV Battery Charging Issues
(Charging Time, Driving Distance, Safety)

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Project Overview – Project Progress

2009	• January: Research Planning by National Science and Technology Council • May: R&D fund support by Ministry of Education, Science and Technology
2010	• March: Completion Ceremony of Seoul Grand Park Pilot Test System • April: R&D fund support by Ministry of Knowledge and Economy • November: Time Magazine's 2010 Best Inventions
2011	• July: OLEV Tram Commercial Operation at Seoul Grand Park • November_ R&D fund support by Ministry of Land, Transport and Maritime Affairs
2012	• May-August: Demonstration Operation for OLEV Bus in Expo 2012 Yeosu Korea • September: Certification of Power Infrastructure and OLEV Bus Commercial Operation for OLEV Bus at KAIST Campus
2013	• February: The top 10 Emerging Technologies 2013 by World Economic Forum • June: Demonstration of 60kHz SMFIR Technology with its Application to Catenary-Free Trams (200 kW)
2014	• March: Demonstration of 60kHz SMFIR Technology with its Application to High Speed Train(1 MW) Commercial Operation of OLEV Bus in Gumi City Area • December: Sustainable Development Award in 2nd UIC (International Union of Railways) Innovation Awards
2015	
2016	• May: Wireless Railway Project Continued (2nd Year)

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R&D Achievements

		2009 MEST * [Core technology]	2010-2011 MKE* [Practical technology]	2012-2013 MLTM* [Commercialization]
Outcome		• Development of original power supply and collection technology • Implementation and verification of core technology	• Improving core technology • Development of common-core technology to verify usability	• Construction of standard power supply infrastructure and bus system • Commercial operation of OLEV bus and infrastructure by local governments (2013)
Cost		25 million	15 million	20 million
Specification	Air Gap	20 cm	20 cm	20 cm
	Efficiency	Max. 72%	Max. 80%	Max. 85%
	Power Capacity	60kW	75kW	100kW
Patents		•Domestic : 125 •Foreign : 9	•Domestic : 127 •Foreign :52	•Domestic : 12 •Foreign : 3

*** MEST : Ministry of Education, Science and Technology   * MKE : Ministry of Knowledge Economy   * MLTM : Ministry of Land, Transport and Maritime Affairs**

Previous Work (PATH Project in California)

Institute of Transportation Studies

California Partners for Advanced Transit and Highways (PATH)

(University of California, Berkeley)

Year 1992 *Paper UCB-ITS-PRR-92-3*

Research Reports

Feasibility Study Of Advanced Technology Hov Systems: Volume 2a: Feasibility Of Implementing Roadway Powered Electric Vehicle Technology In El Monte Busway: A Case Study

Ted Chira-Chavala Edward H. Lechner

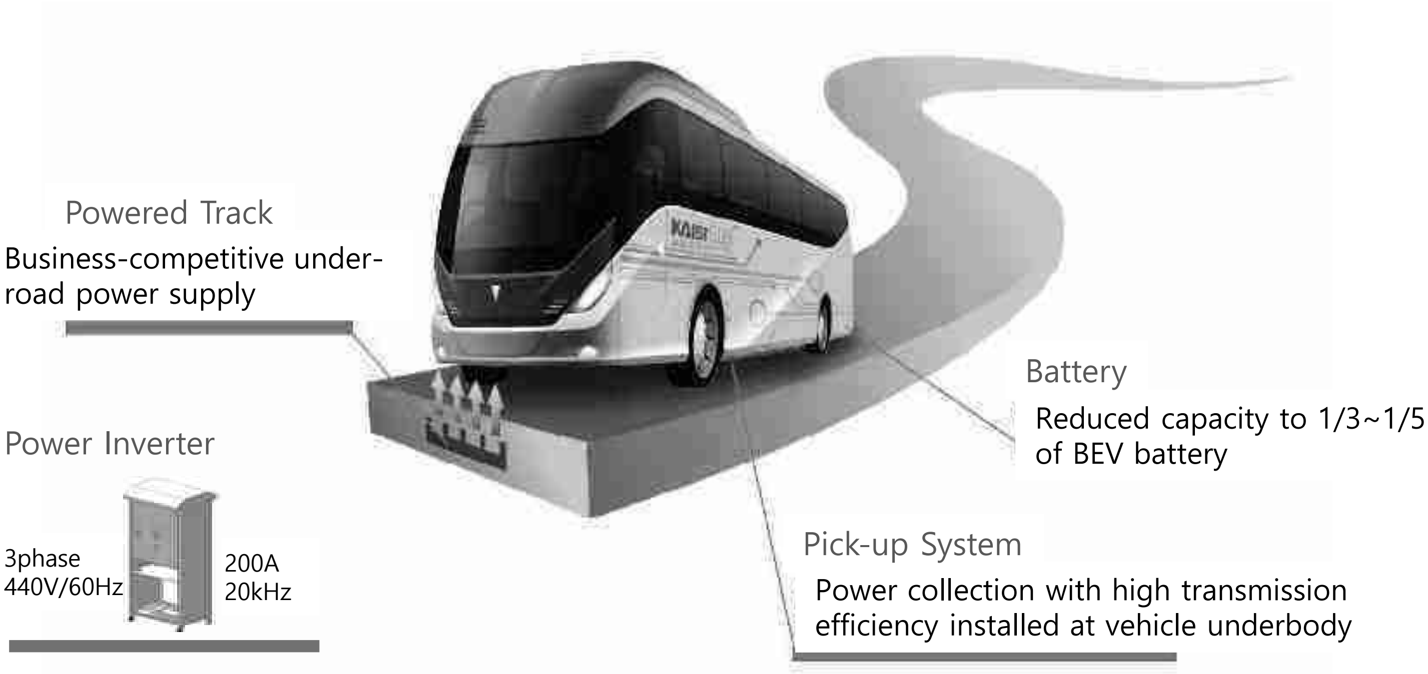
Dan M. Empey

Comparison of WPT Technologies in Vehicles

Field	Institute	Charging Type	Contents
Vehicle	PATH	Charging during stop and driving	- Air gap : 7.5cm - Efficiency : 60% - Capacity : 60kW 
	Wampfler	Charging at stop	- Air gap : 3cm - Efficiency : 86% - Capacity : 60kW(30kW x 2) 
	Showa	Charging at stop	- Air gap : 10cm - Efficiency : 92%(30,60kW), 93%(150kW) - Capacity : 30kW, 60kW, 150kW 
	OLEV	Charging during stop and driving	- Air gap : 20cm (35cm: core to core) - Efficiency :Max. 85% - Capacity : 100kW - EMF Level : below 6.25 μT

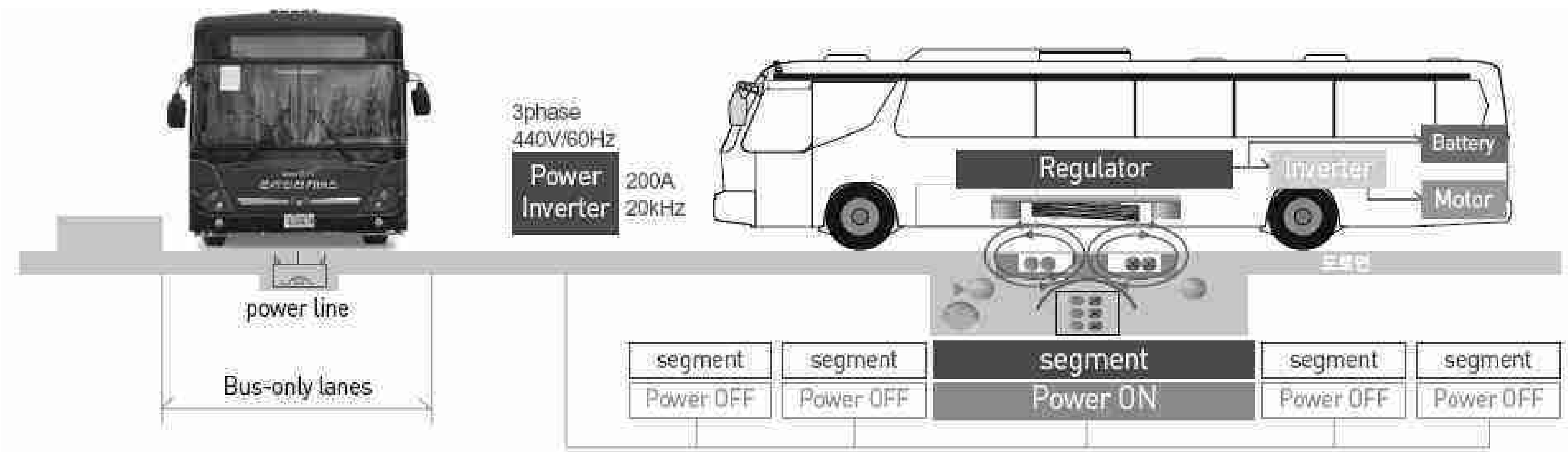
Project Overview – Concept

Solving battery and charging problems by developing OLEV, which enables wireless electric power transmission while vehicle is stopping or running.



A pickup device installed under the vehicle works to collect the magnetic field from power cables laid under the road and convert it into electric energy for vehicle operation.

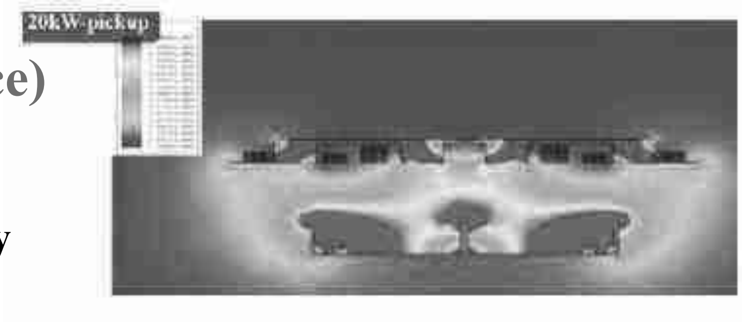
Principle & Core Technology – Principle



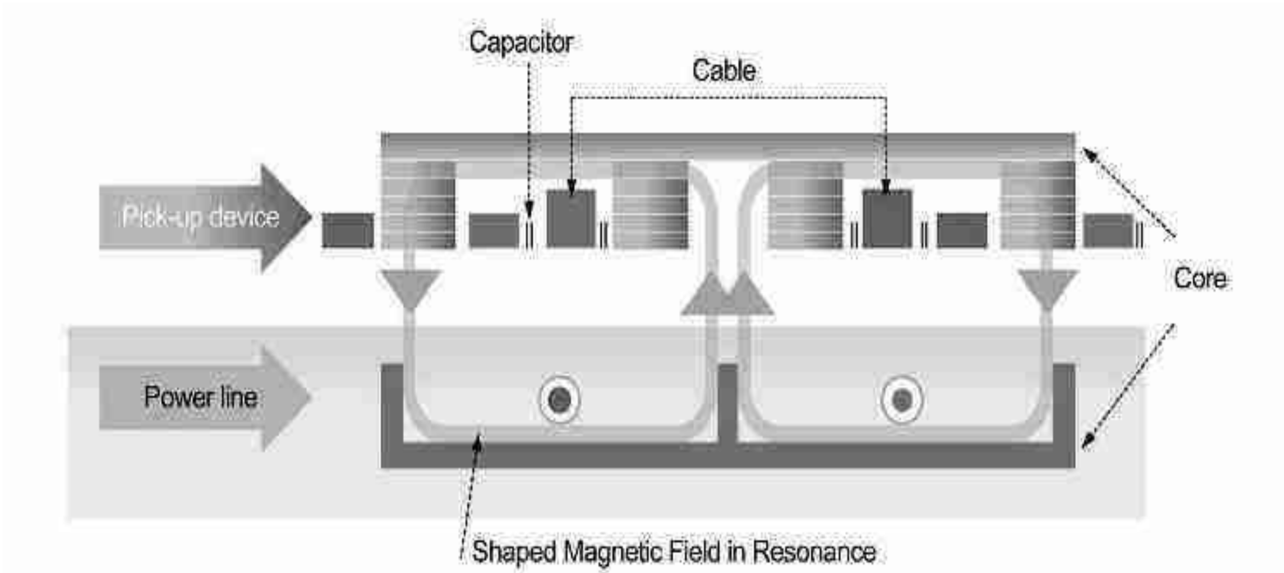
Power inverter	Road embedded power line	Pickup module	Regulator
•Generate high-frequency current •High-efficiency resonant control	•Meet safety standards for EMF	•Installed under vehicle •Contactless power transfer	•Battery charge or motor driving •Charging while stopping or driving

Principle & Core Technology – Core Technology

- **Acquisition of core technology :**
  SMFIR(Shaped Magnetic Field in Resonance)

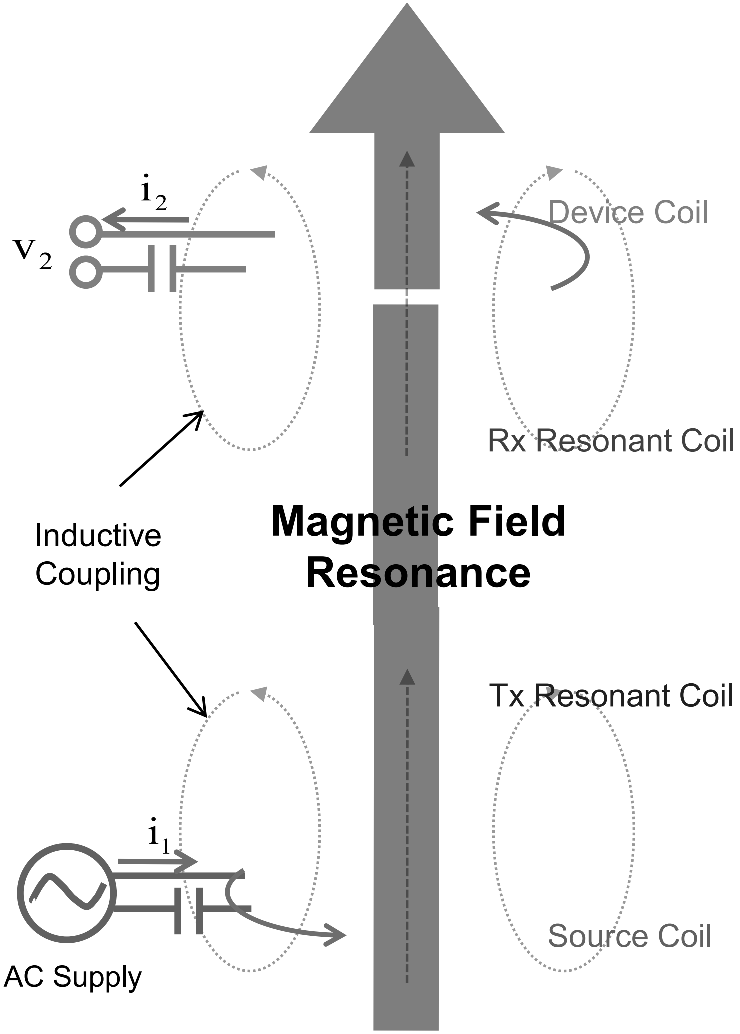


- **The SMFIR is "Shaped Magnetic Field in Resonance" technology, which safely delivers high amounts of energy to an electric vehicle while it is stationary or in motion.**



Source Current → **Amperes law** → **Magnetic flux B** (travels through air) → **Faradays law (induction)** → **Generate Voltage**

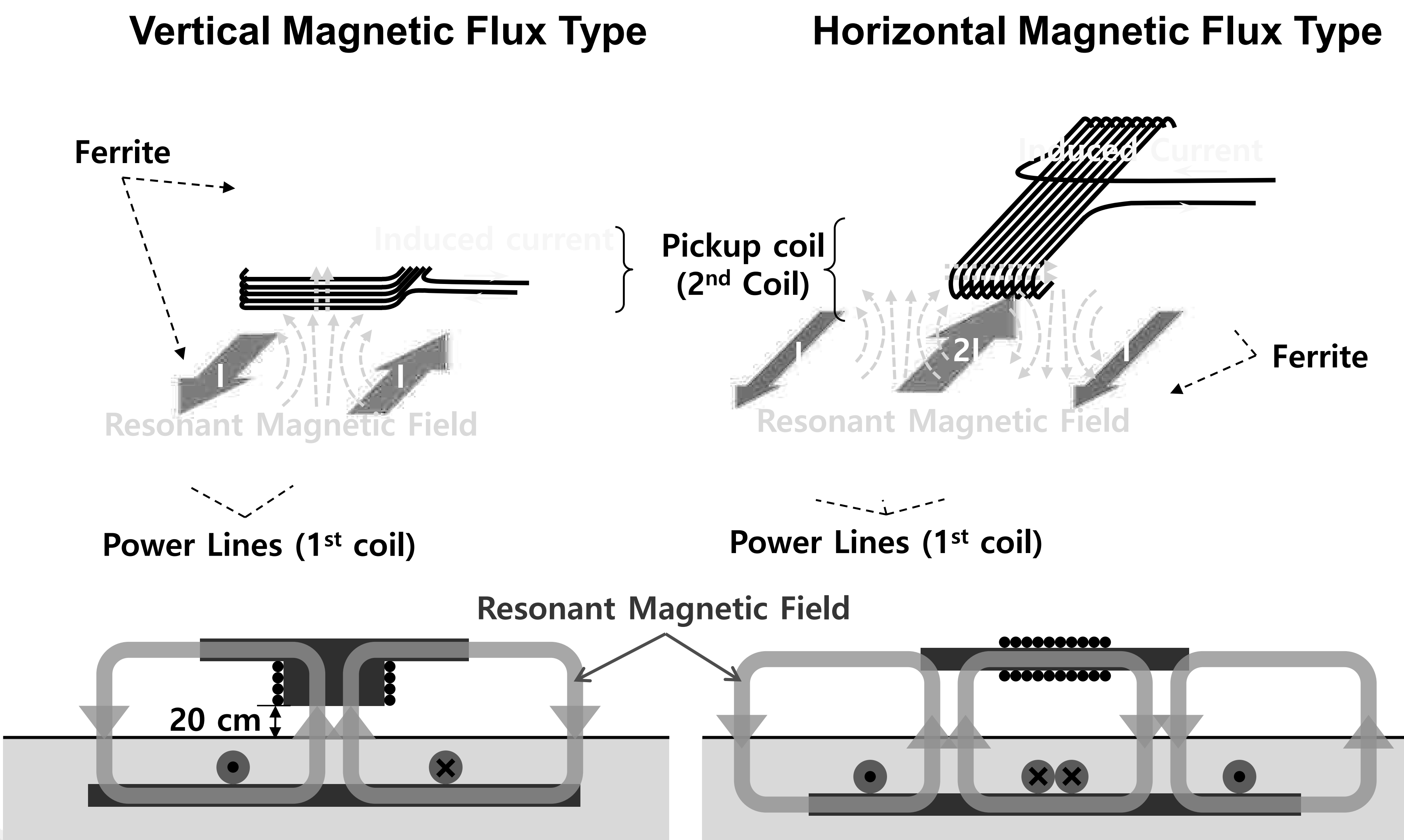
Mechanism of Wireless Power Transfer



$$v_2 = j\omega M i_1$$

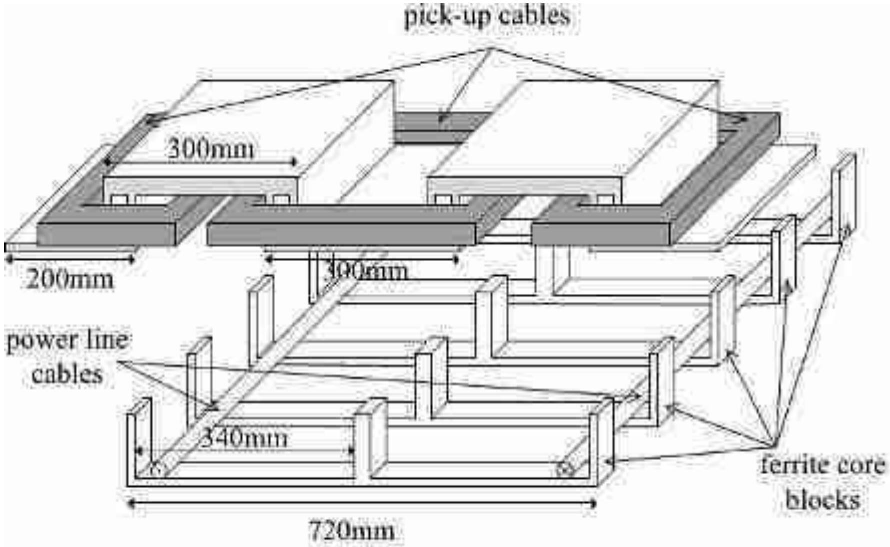
- Voltage induced at port 2
- Matching circuit for resonance
- Design Parameters: Power circuits, Magnetic field design, Frequency
- Feedback by i_2
- Maximum power transfer at resonance frequency

Coil and Core Design for Dynamic/Static Wireless Charging



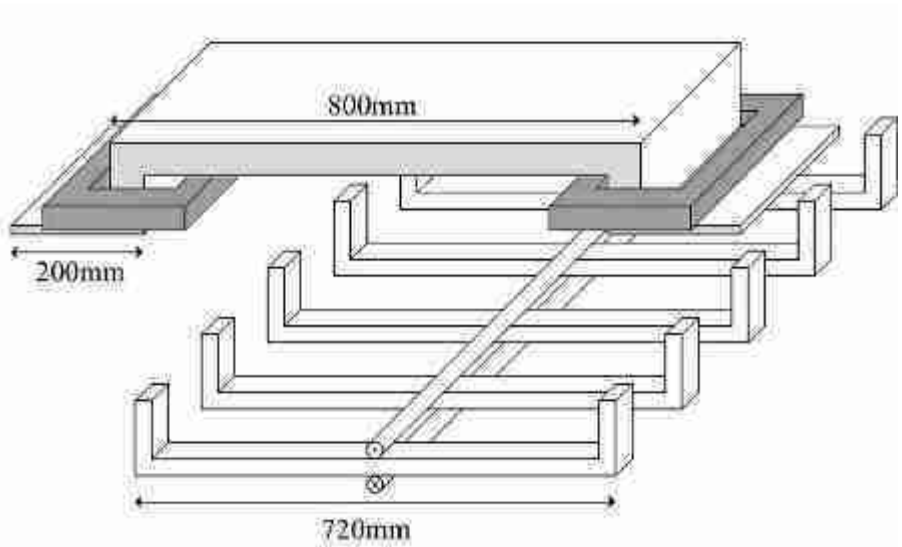
Coil and Core Design for Dynamic/Static Wireless Charging

Type I

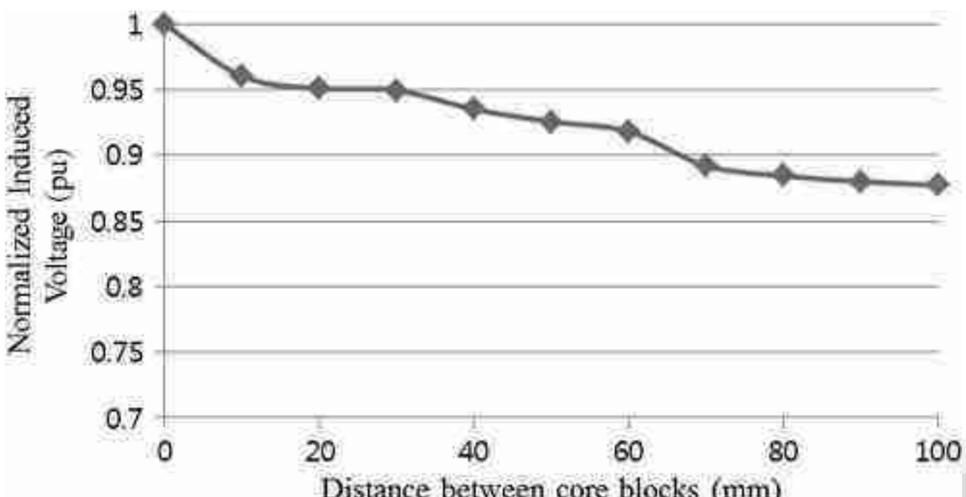


High Induced Voltage

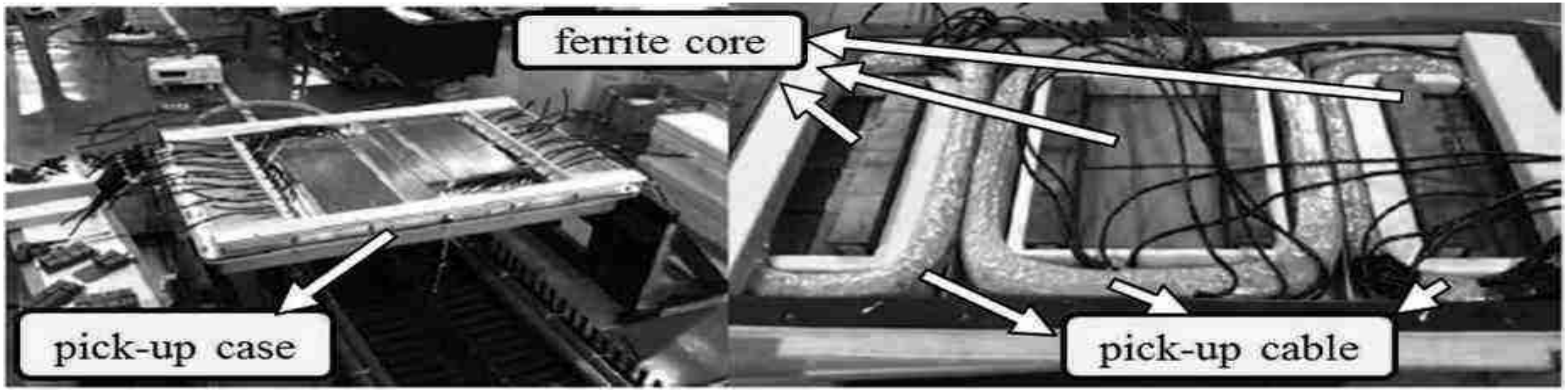
Type II



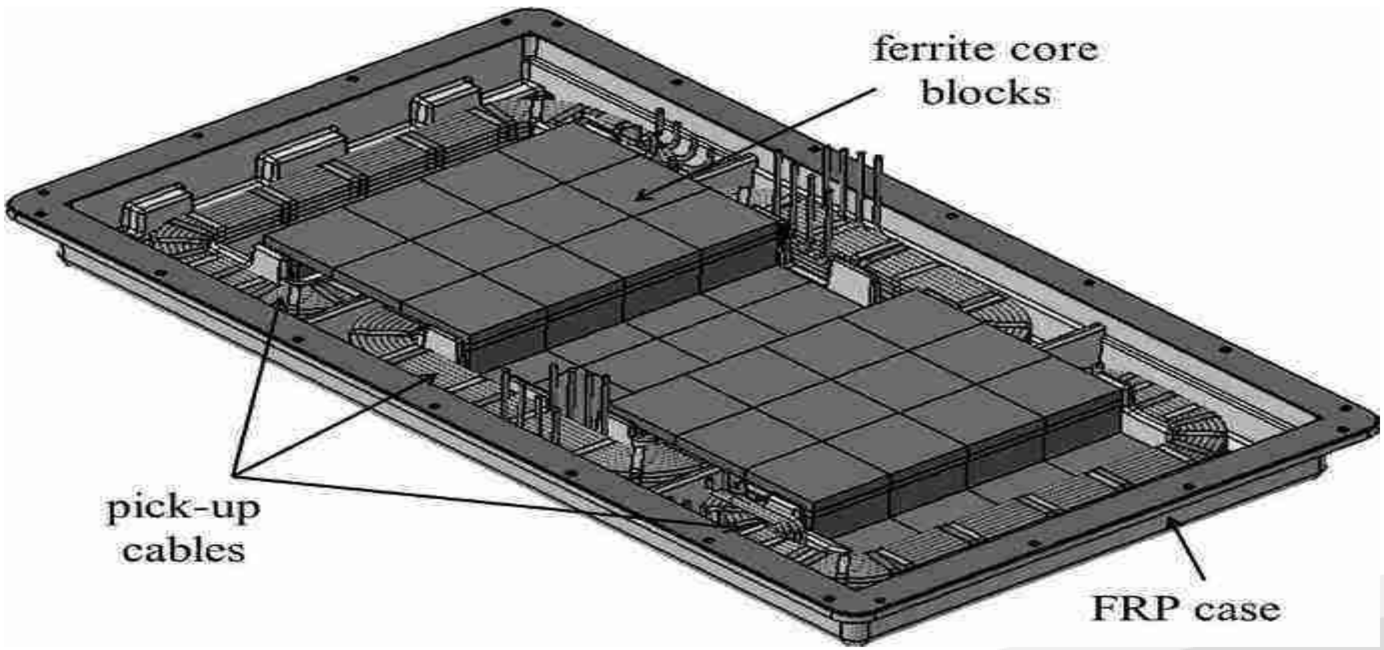
Lateral Displacement Tolerance



Pickup System

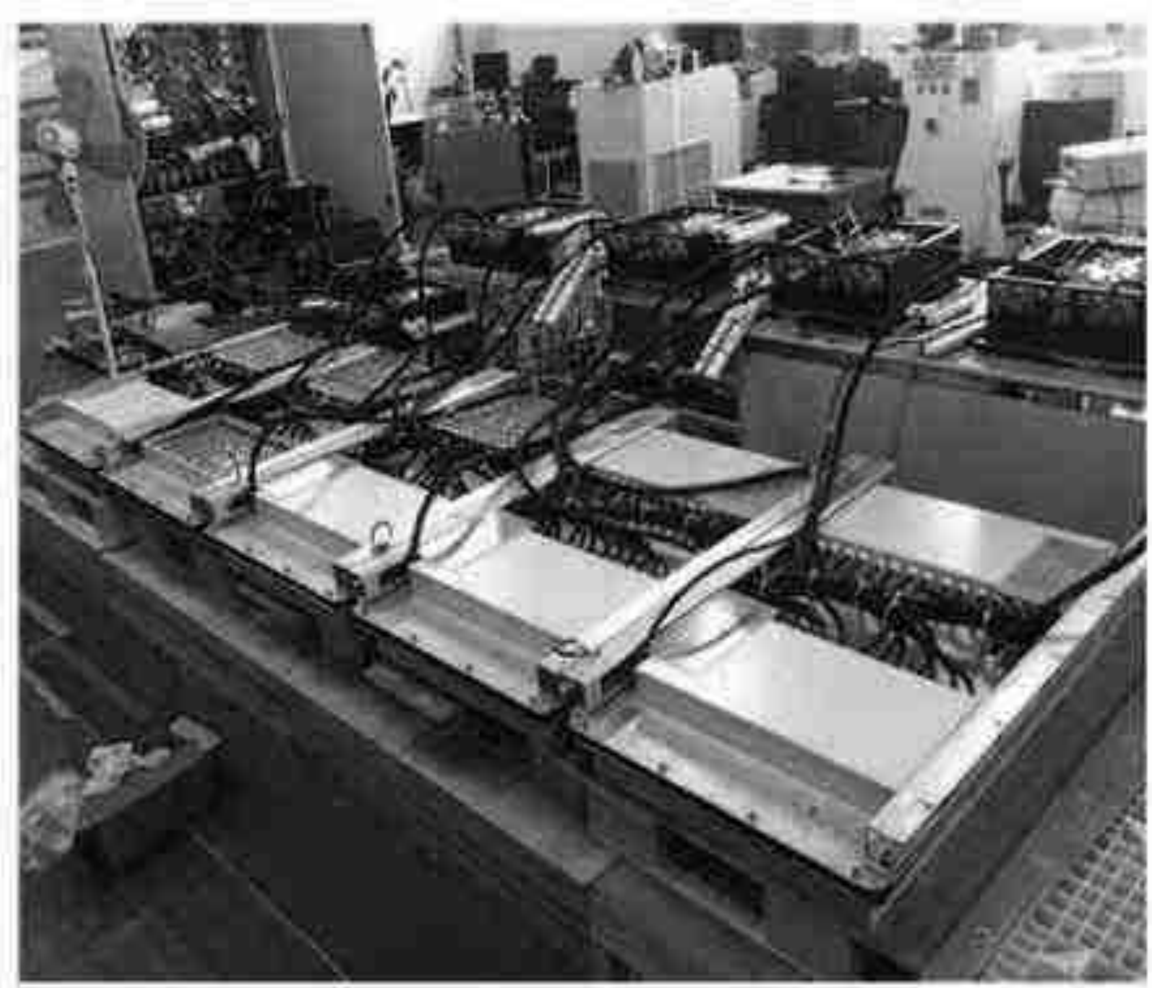


Implementation of pickup module



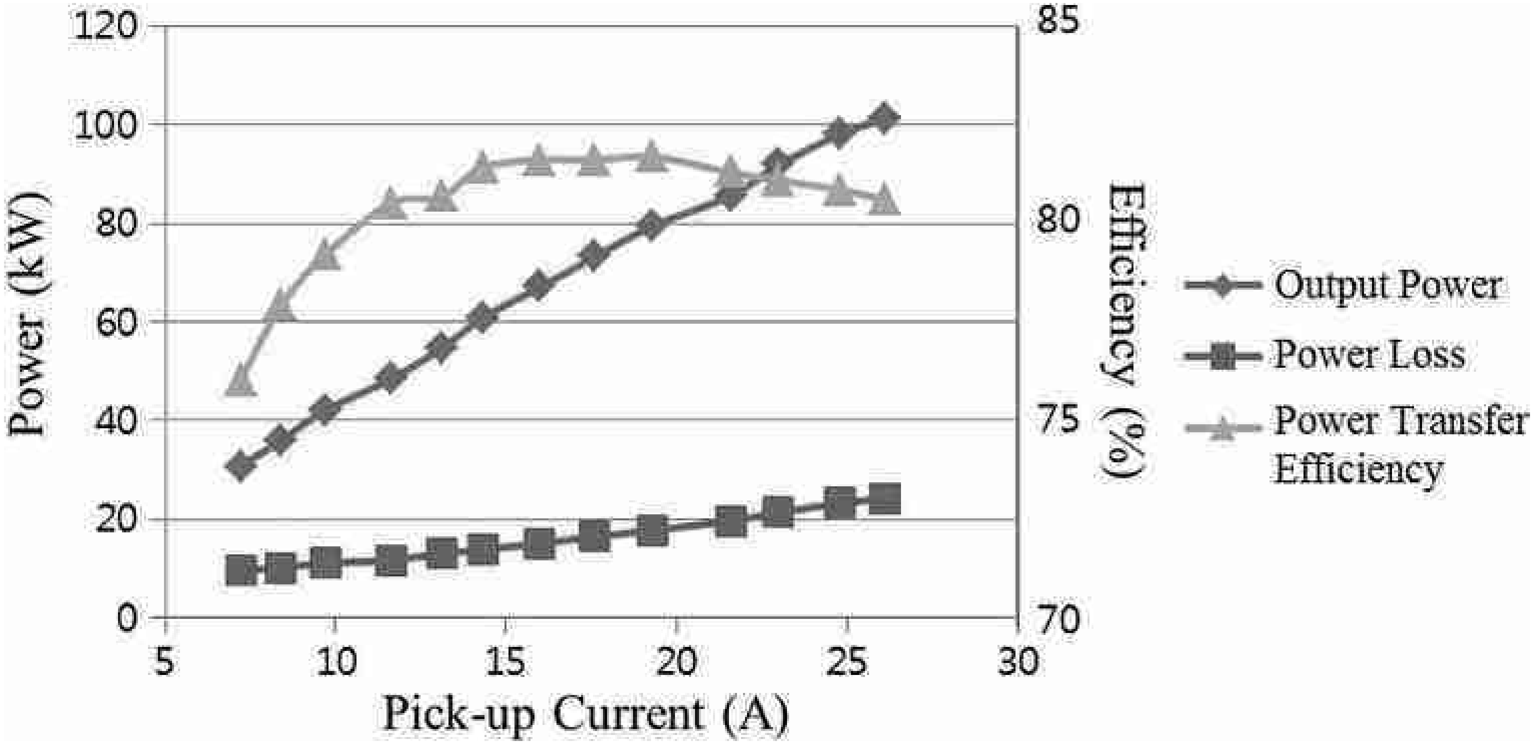
Mechanical structure of pickup module

Pickup Modules for Wireless Charging Electric Bus



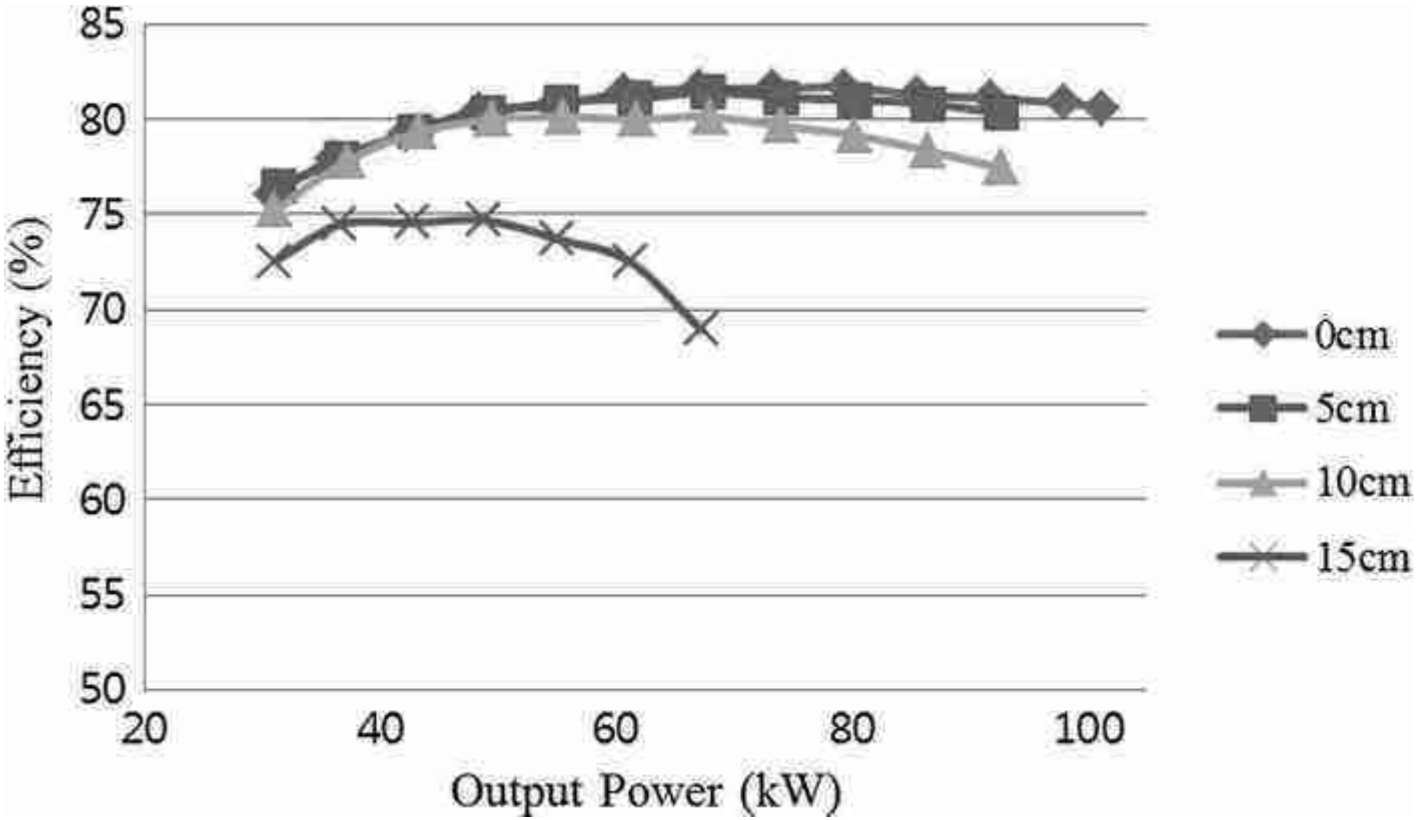
Power supply and pickup system implemented in laboratory

Output Power and Efficiency

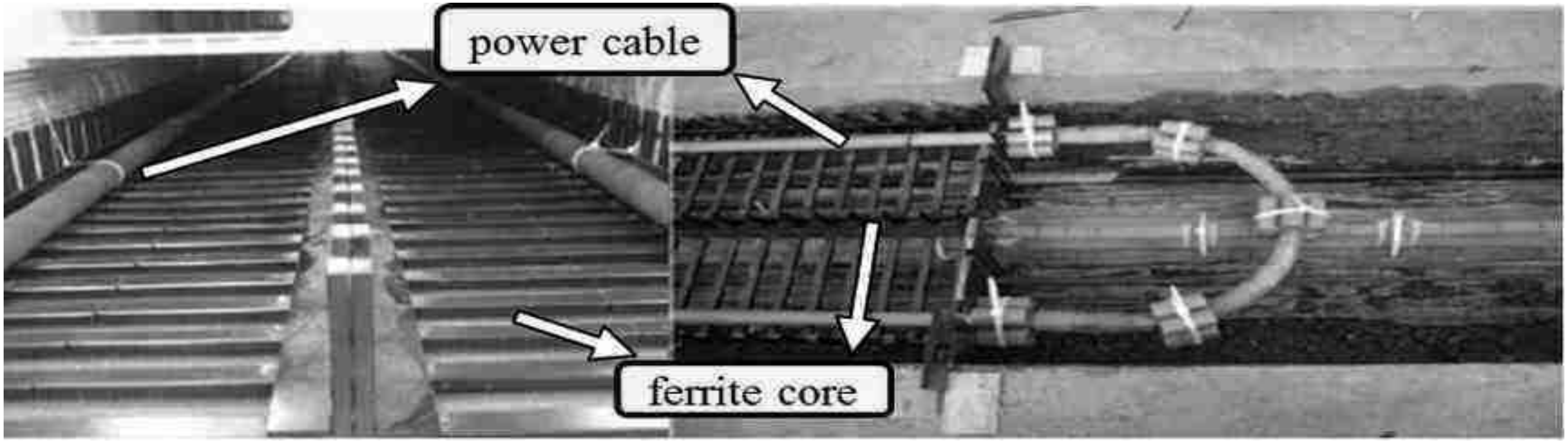


Output powers, power loss, and power transfer efficiency as functions of pickup current

Effect of Lateral Displacement on the Efficiency



Power Line Module



Implementation of power line module

Pre-casting concrete type of power line module

Wireless Charging Technology for Bus Operation

	Origin	**Acceleration**	**Constant driving**	**Deceleration**	**Destination**
Driving mode					
	Charging while stopped	Charging while driving	Battery powered	Regenerative braking	Charging while stopping
Features	- Installation ratio of power supply line is below 20%				
	- Power loss is minimized by applying segmentation control technology to power supply lines				
	- No extra time is required for recharging battery because of real time wireless charging				
	- Safe and convenient charging				

R&D Achievements

Contents	Progress	Remarks
Electromagnetic Field	Completion of frequency allocation (20kHz, 60kHz)	KCC (Korea Communications Commission)
Road Structure	Revision of the road decree allowing power line installation	MLTM (Minister of Land, Transport and Maritime Affairs)
Electrical Safety	Electrical safety standards for OLEV power supply system Private region / Public region	MKE (Ministry of Knowledge Economy)
Vehicle Certification	OLEV vehicle safety standards Private region / Public region	MLTM (Minister of Land, Transport and Maritime Affairs)

OLEV Systems in Korea

Seoul Grand Park (July 2011)

Installation: 372.5m(16%) of total 2.2 km

Yeosu Expo 2012 (May~Aug. 2012)

Installation: 36m(3%) of total 1.2 km

OLEV Shuttle Bus at KAIST (Oct. 2012)

Installation: 60m(1.6%) of total 3.76 km

Gumi City (March 2014)

Installation: 144m(0.6%) of total 24km

Sejong City (June 2015)

Commercialization Strategy

Bus centered public Transportation system

- Verifying the economic feasibility and safety through the bus-centered public transportation market
- Installation of power supply line near the stopping and intersection place

Railroad(KTX) systems

- Maximizing the charging efficiency by minimizing air gap
- Solving the speed constraint problem of railroad (KTX etc) and reducing tunnel construction cost

Passenger car

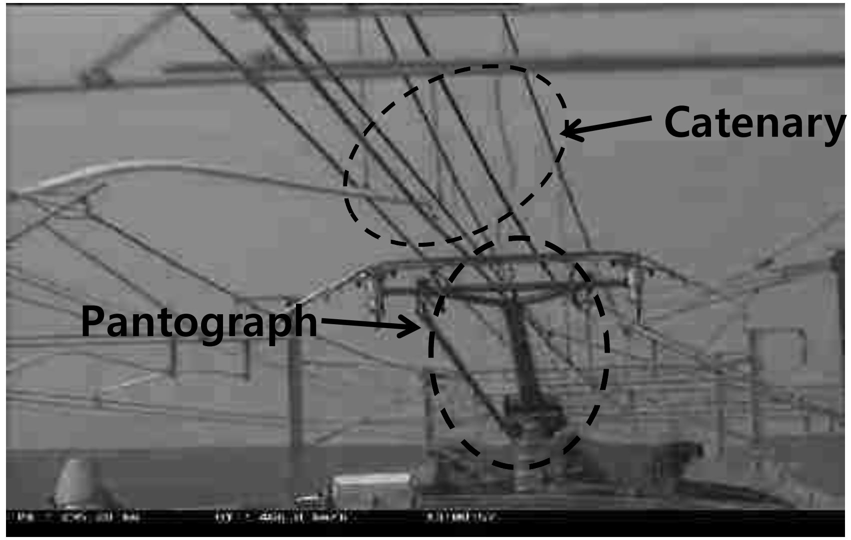
- Sharing of online electric bus infrastructure
- Utilizing the proven technology and marketability obtained through the bus and railroad project

Wireless Charging Infrastructure Projects

(Public parking lot, shopping mall parking lot and taxi stop area)

WPT in Railway System

Application of Wireless Power Transfer in Railway System

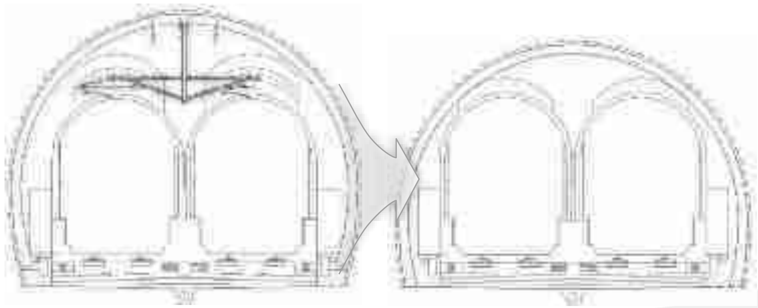


Railway Application of WPT Technology

- **Social Effect**
  Every year in Korea, 13.2 people lose their lives due to high power overhead lines.


전철 고압선에 감전돼 중태
전철역고압선에 감전 고교생 중화상

- **Economic Effect**
  Tunnel Size Reduction (85.7m^2 → 74.5m^2)
  Construction Cost: 5% Reduction

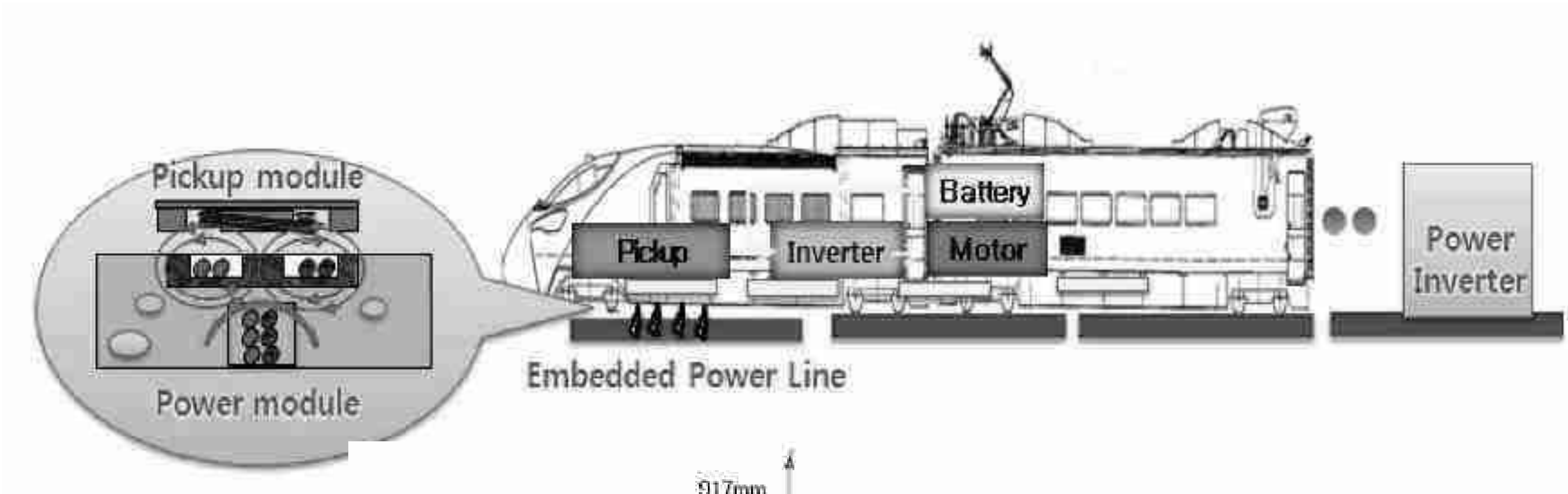


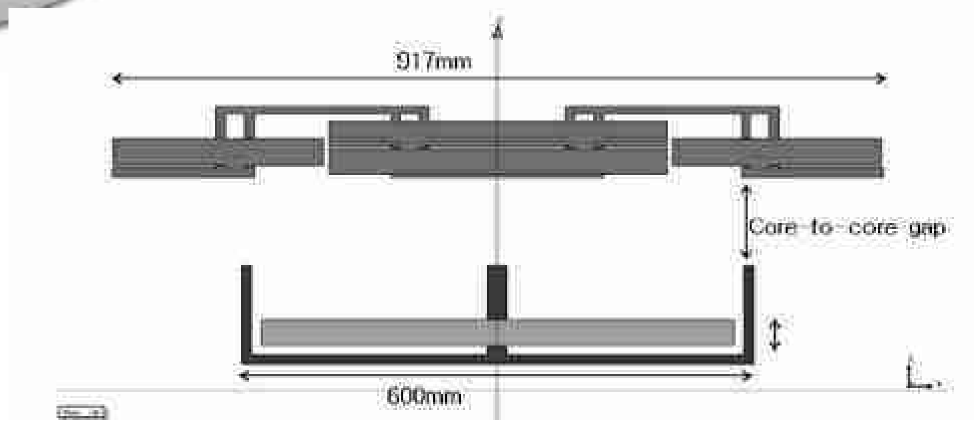
Railway Application of WPT Technology

- **Comparison with Third Rail System**

Power Supply	Cost ($/km)
Third Rail	1,800,000
Wireless Power	750,000

Design of Wireless Power Transfer System



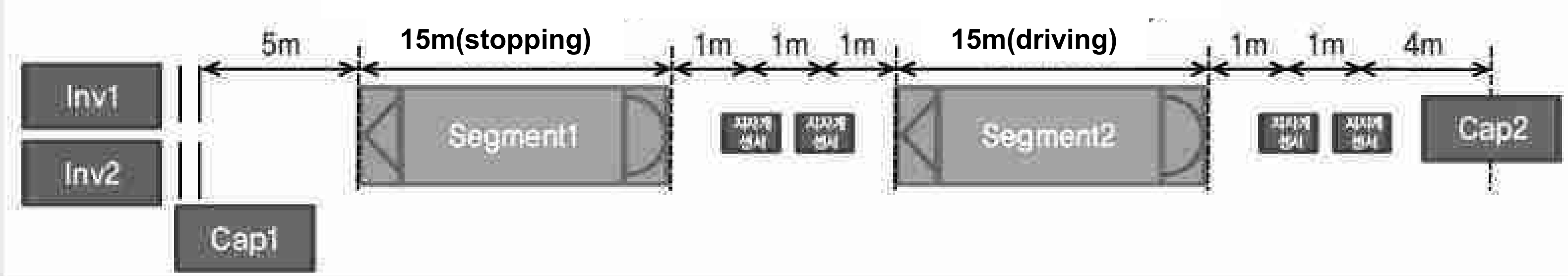


- ❑ Smaller core-to-core gap and no lateral displacement in railway system.
- ❑ Higher frequency for higher power with low current.

Osong Wireless Power Railway Test Site

◈ **Held a demonstration of 60kHz power supply and pickup technology at the Osong Catenary-free Test Course, with its application to catenary-free trams(Jun. 4, 2013)**

<Pick up>

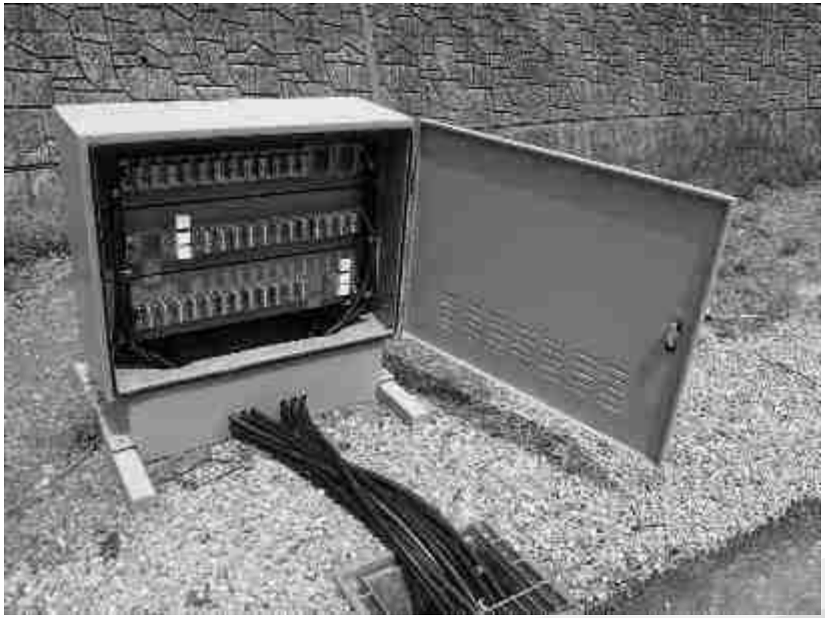


WPT for Tram – Configuration of Power Line Module

- **Transmitter track and tuning capacitors → Tuned at 60 kHz**

Capacity	200 kW	**Rated current**	66.6 A_{rms}
Switching frequency	60 kHz	**Segment length**	15 m
No. of coil turns	6	**Efficiency**	> 97 %

Transmitter track

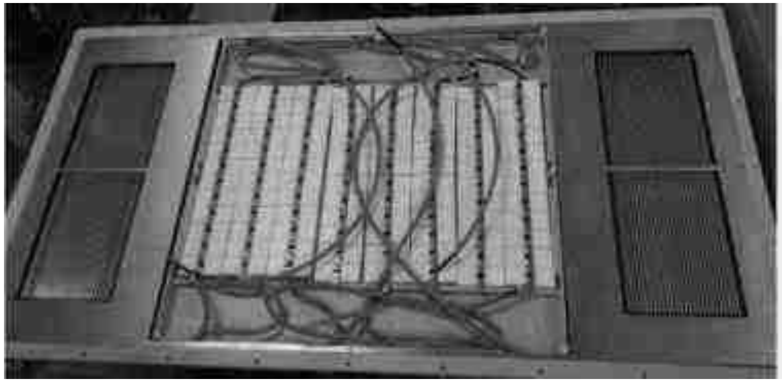


Tuning capacitors

WPT for Tram – Configuration of Pickup Module

- Pickup and tuning capacitors → Tuned at 60 kHz

Rate power	60 kW/module	**Rated output voltage**	AC 600 V@ 60 kHz
Resonance frequency	60 kHz	**Rated output current**	100 A (25 A/CH)
Airgap	7 cm	**Coil structure**	1:2:1 layer



EMC Issues for Vehicular WPT

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EMC Problems in WPT System

❑ Electromagnetic Compatibility (EMC)

EMF
Electromagnetic Field

EMC
Electromagnetic Compatibility

EMI
Electromagnetic Interference

- **Fundamental Frequency**
- **Near Field**

- **Harmonic Frequency**
- **Far Field**

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Standardization of Wireless Power Transfer for EV

- ITU-R (International Telecommunication Union – Radiocommunication)
  - Recommend standard frequency by unanimous approval
  - Considering 100~200 kHz, 6.78 MHz for mobile, 20, 60, 85 kHz for EV, and 2.45, 5.8 GHz for Microwave Power Transmission

- IEC (International Electrotechnical Commission)
  - Organizing regulation and standard of each country
  - JPT61980 TC69 is in charge of WPT EV standardization

- IEC CISPR
  - Reviewing EMI regulation and standard measurement issues from electric system
  - CISPR 11 WG1 TF WPT in charge of WPT EV standardization especially EM radiation

- SAE J2954
  - Non-governmental organization
  - Lead by automotive industry
  - 20 kHz / 60 kHz for Heavy Duty Vehicle, 85 kHz for Light Duty Vehicle

Treatment of Tumor using Electromagnetic Field

www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DeviceApprovalsandClearances/Recently-ApprovedDevices/ucm254480.htm

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Medical Devices

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Recently-Approved Devices
2015 Device Approvals
2016 Device Approvals

NovoTTF-100A System - P100034

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This is a brief overview of information related to FDA's approval to market this product. See the links below to the Summary of Safety and Effectiveness Data (SSED) and product labeling for more complete information on this product, its indications for use, and the basis for FDA's approval.

Product Name: NovoTTF-100A System
PMA Applicant: NovoCure Ltd.
Address: 15022 MATAM Center, Haifa 31905 Israel
Approval Date: April 8, 2011
Approval Letter: http://www.accessdata.fda.gov/cdrh_docs/pdf10/p100034a.pdf

What is it? The NovoTTF-100A System treats recurrent glioblastoma multiforme (GBM). The NovoTTF-100A System is a portable battery or power-supply operated device which produces changing electrical fields, called tumor treatment fields ("TTFields") within the human body. TTFields are applied to the head of the patient by electrically-insulated surface electrodes.

How does it work? TTFields stop the growth of tumor cells resulting in cell death of the rapidly dividing cancer cells. The geometrical shape and scattering of the electrical charges within the dividing tumor cells allows TTF electrical fields to physically break up the tumor cell membrane. The frequency of the TTFields used for a particular treatment is specific to the size of the cell type being treated.

When is it used? The NovoTTF-100A System is intended as a treatment for adult patients (22 years of age or older) with confirmed glioblastoma multiforme, following confirmed recurrence in an upper region of the brain (supratentorial) after receiving chemotherapy. The device is intended to be used as a stand-alone treatment, and is intended as an alternative to standard medical therapy for recurrent GBM after surgical and radiation options have been exhausted.

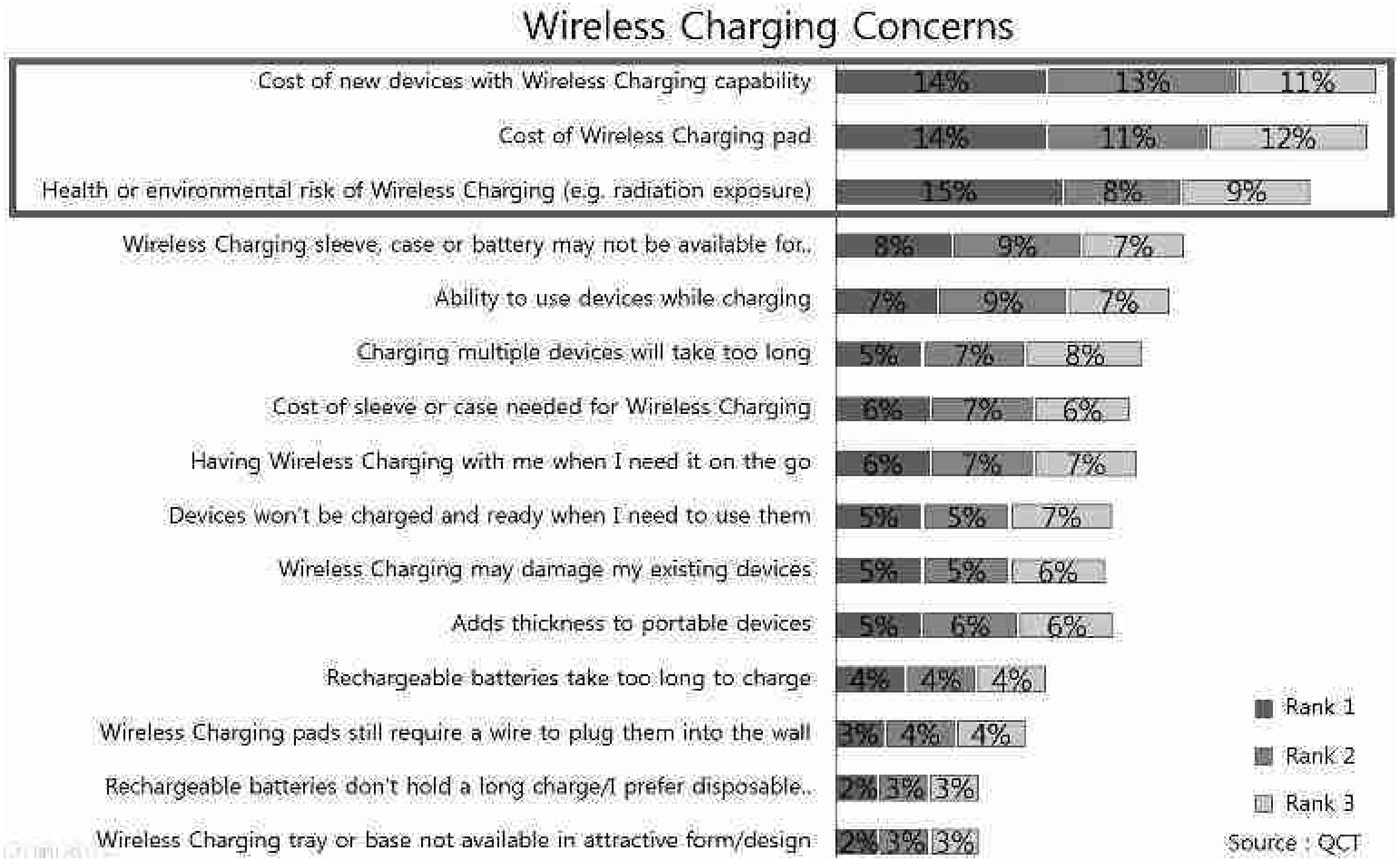
Introduction – Biological Effect from Electromagnetic Field

❑ Concerns on Electromagnetic Field

Group 1	*Carcinogenic to humans*
Group 2A	*Probably carcinogenic to humans*
Group 2B	*Possibly carcinogenic to humans*
Group 3	*Not classifiable as to its carcinogenicity to humans*
Group 4	*Probably not carcinogenic to humans*

Lyon, France, May 31, 2011 - The WHO/International Agency for Research on Cancer (IARC) has classified radiofrequency electromagnetic fields as possibly carcinogenic to humans (Group 2B), based on an increased risk for glioma, a malignant type of brain cancer, associated with wireless phone use.

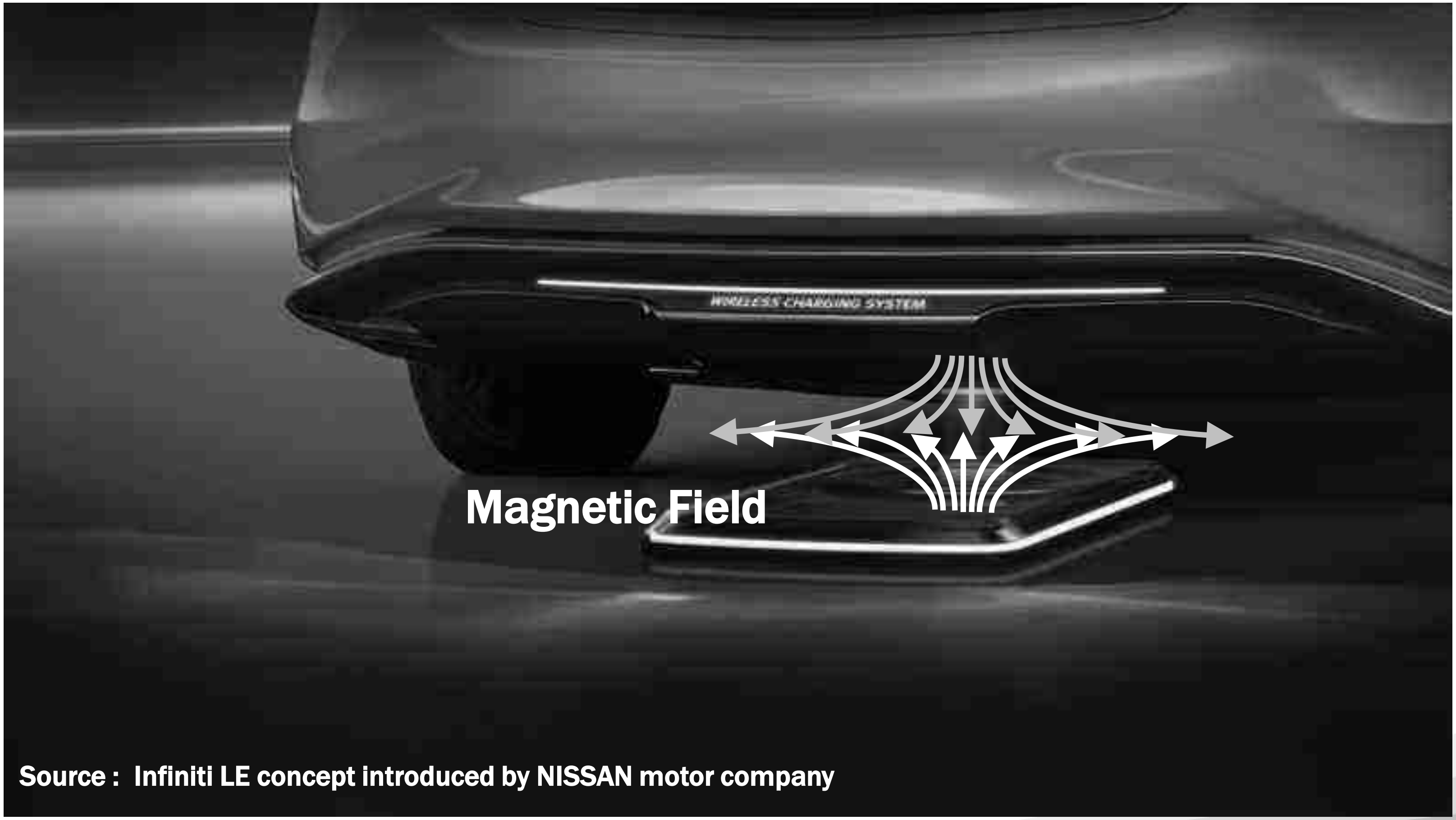
Concerns on Wireless Charging System



- Cost of new devices and the wireless charging pad top the list of concerns for consumers.
- There is a fair amount of concern over **the health and safety risks** as well.

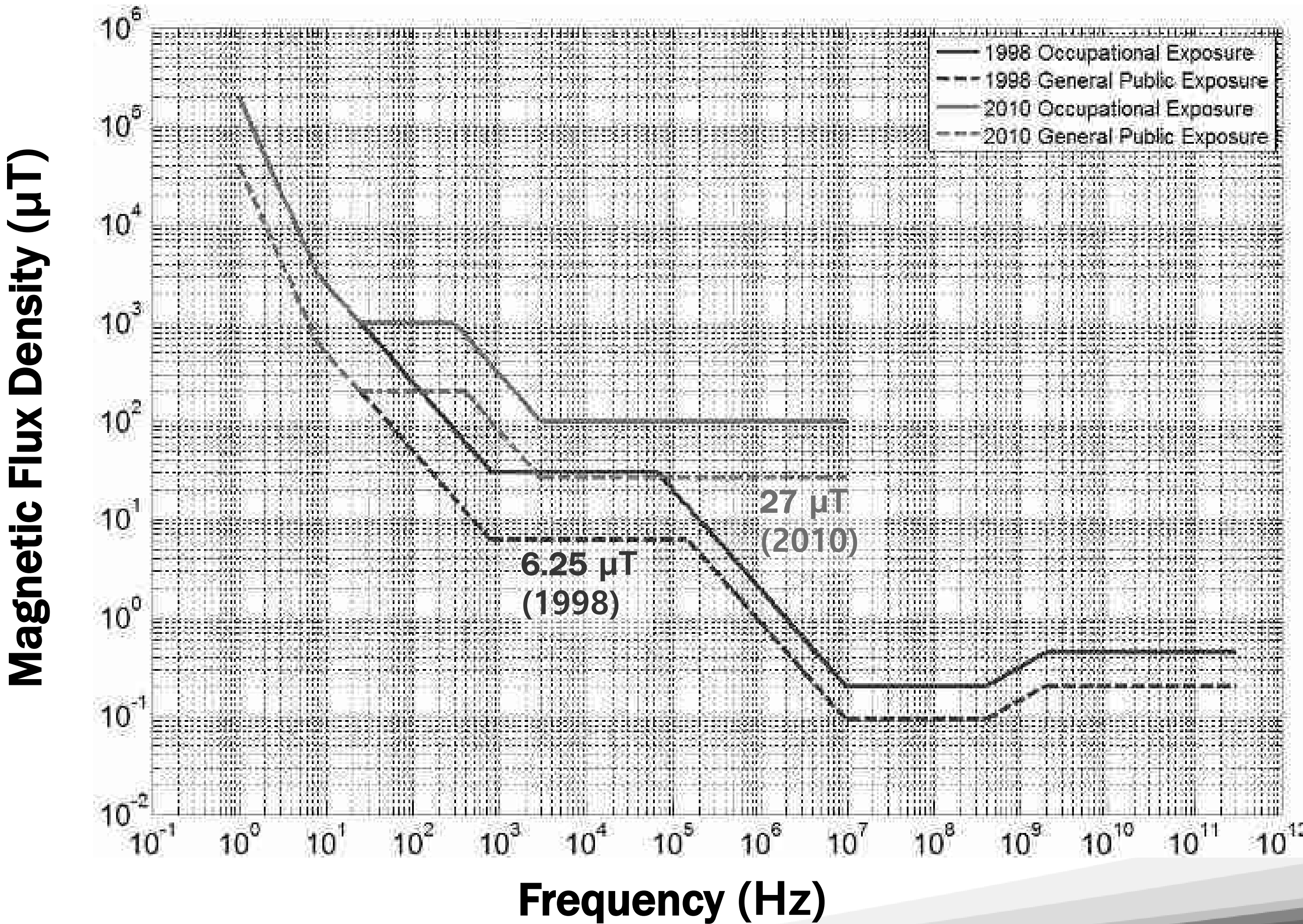
Electromagnetic Shielding

- **Applications of WPT to EV is being developed actively by leading companies.**



EMF Regulations

- Guidelines of time-varying magnetic fields by ICNIRP



EMF Measurement – IEC 62110

3.1
single-point measurement
procedure to measure the field level at a specified height, used for uniform fields

NOTE The conditions under which the field can be considered as uniform or non-uniform are given in section 5.1.

3.2
three-point measurement
procedure to measure the field levels at three specified heights at a single location, used for non-uniform fields

NOTE In the case where the safety standard does not allow spatial averaging (such as [2]), then the maximum of the three measured values should be used.

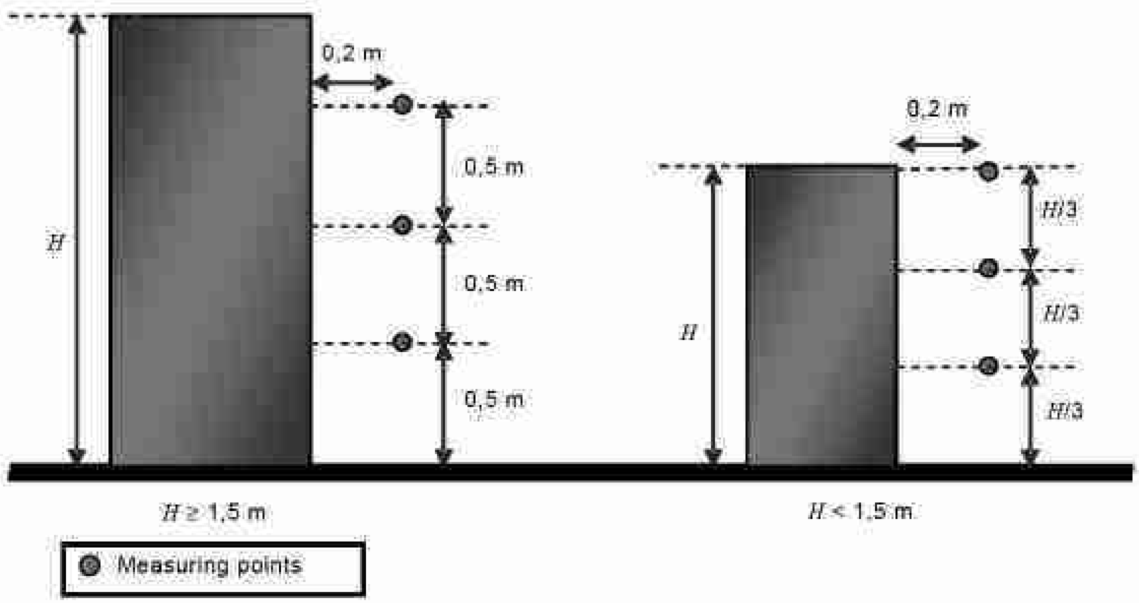
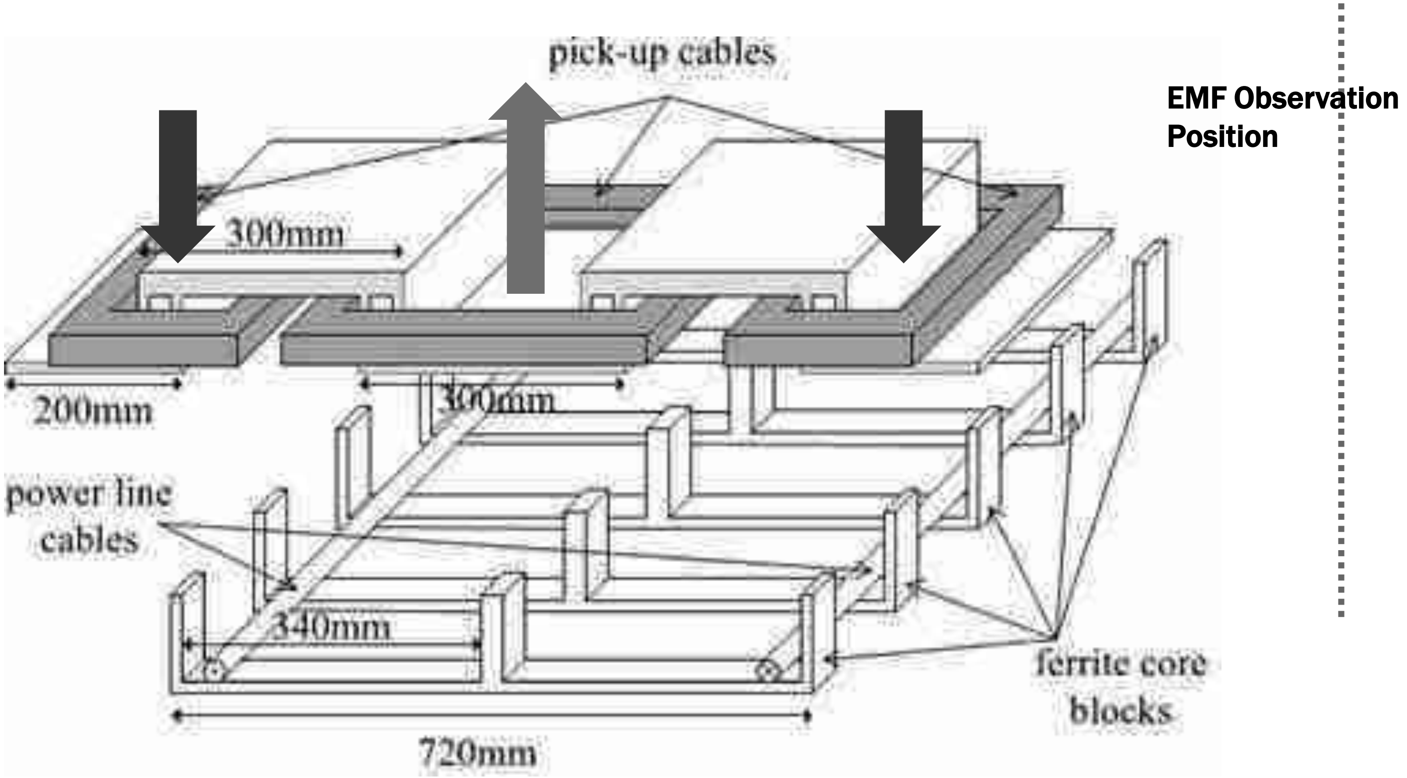


Figure 1 – Heights of *the three-point measurement*

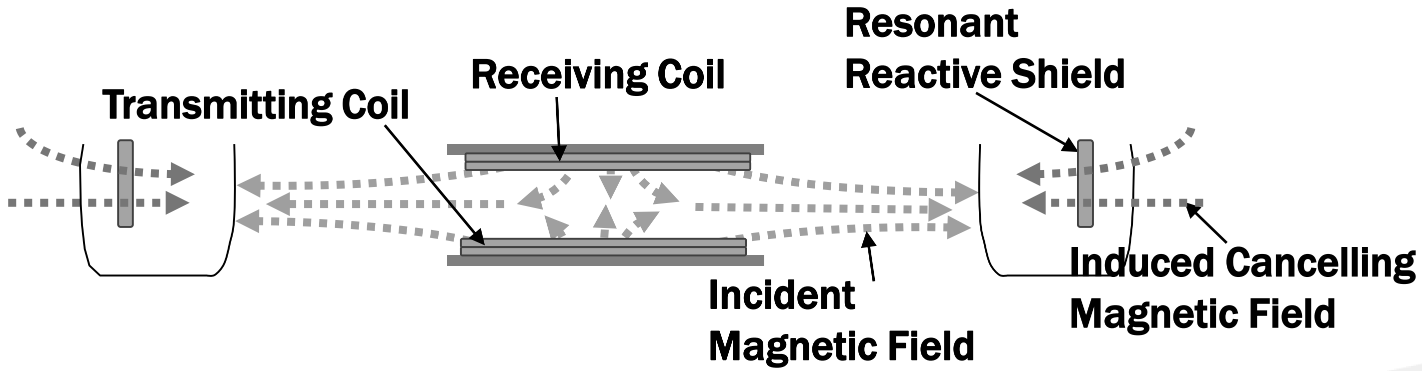
EMF Reduction using Magnetic Material

❑ Balancing with Coil and Magnetic Material



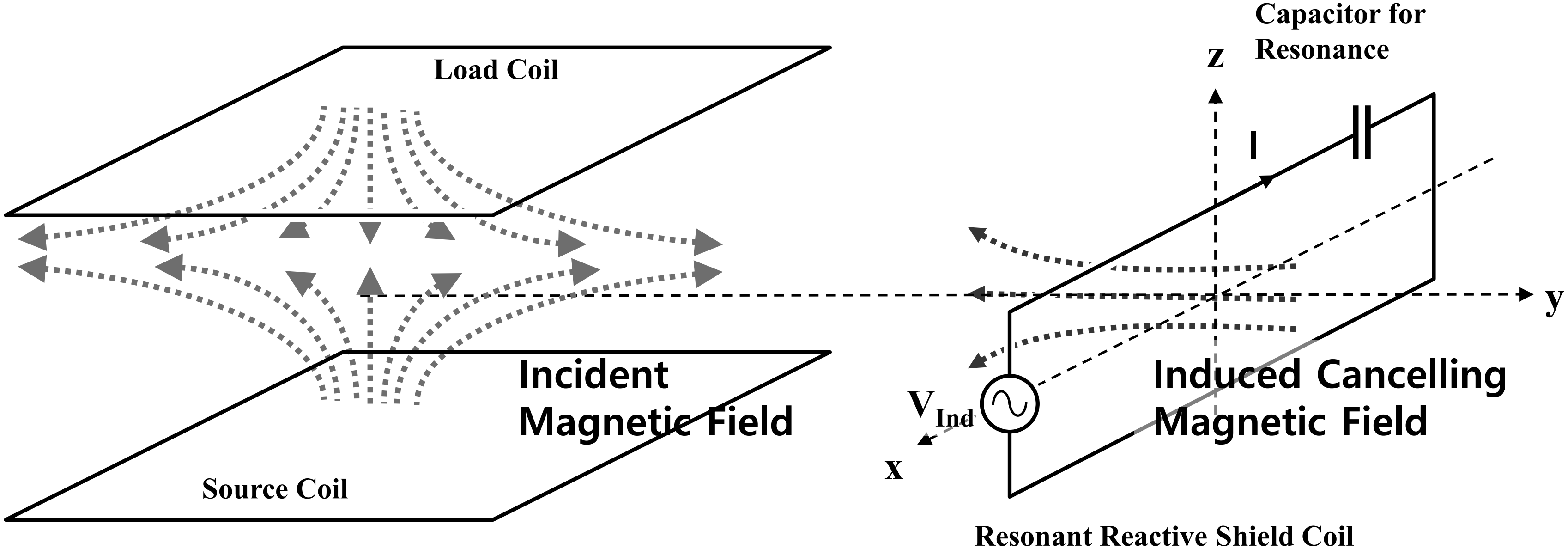
Electromagnetic Shielding

- **Generation of electromagnetic field (EMF) and shielding**



Reactive Shielding Coil – Type 1

- **The principle of the EMF Cancellation by using reactive shield**

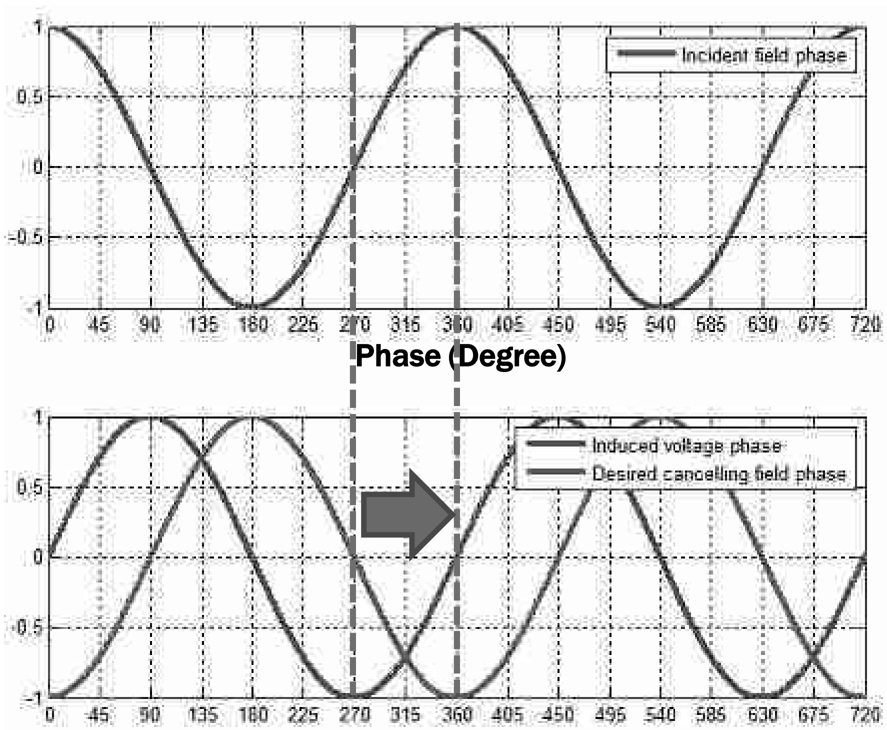


$$I_{sh} = \frac{V_{ind}}{Z_{sh}} = \frac{V_{ind}}{\left(j\omega L_{sh} + \frac{1}{j\omega C_{sh}}\right) + R_{sh}}$$

S. Kim, H. H. Park, J. Kim, J. Kim, and S. Ahn, "Design and Analysis of a Resonant Reactive Shield for a Wireless Power Electric Vehicle," IEEE Trans. on Microwave Theory and Techniques, Vol. 62, No. 4, pp.1057-1066, Apr. 2014.

Desired Phase for Maximum Cancellation

Desired phase of the resonant reactive shield current



Phase (Degree)

0 deg — **Incident field (Reference)**

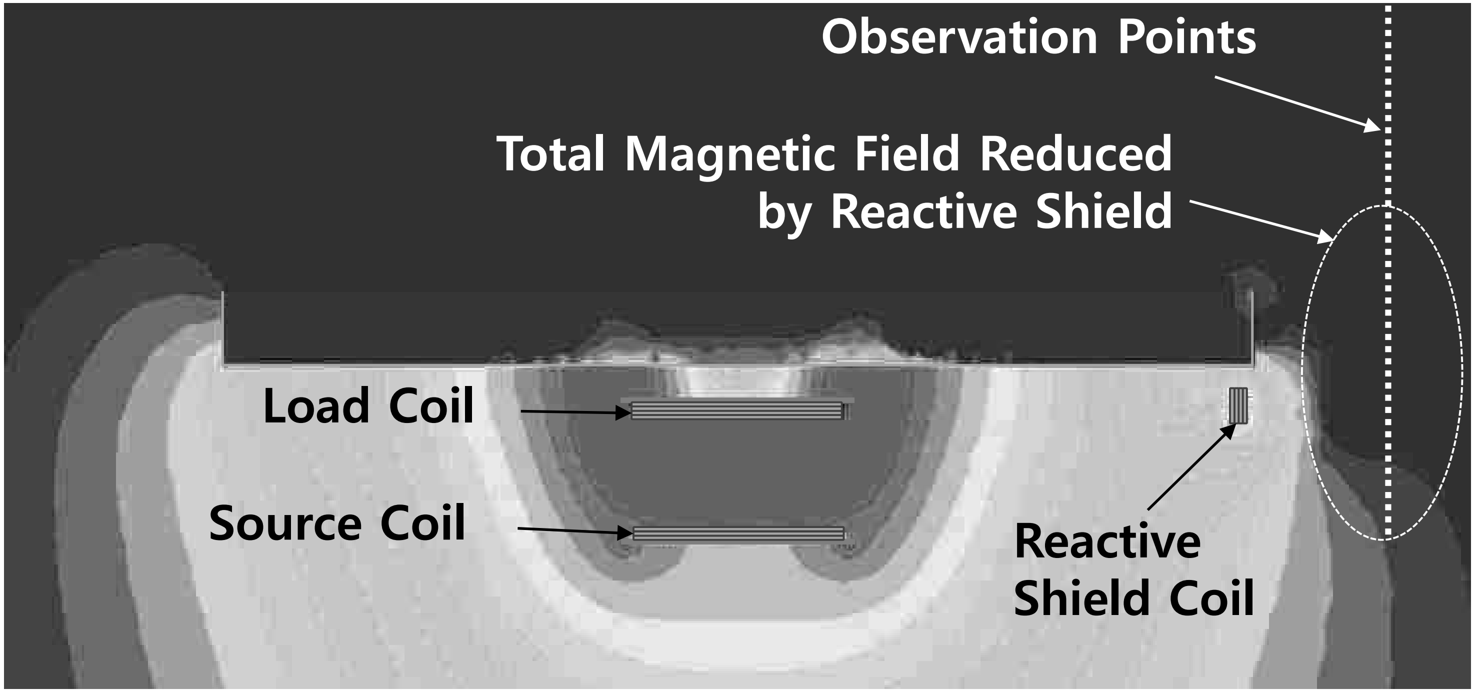
90 deg — **Induced voltage (90-degree phase delay)**

180 deg — **Desired Cancelling field (additional 90-degree phase delay)**

- 180-degree phase difference is best condition for maximum cancellation.
- Resonant reactive shield current needs **additional 90-degree phase delay**.

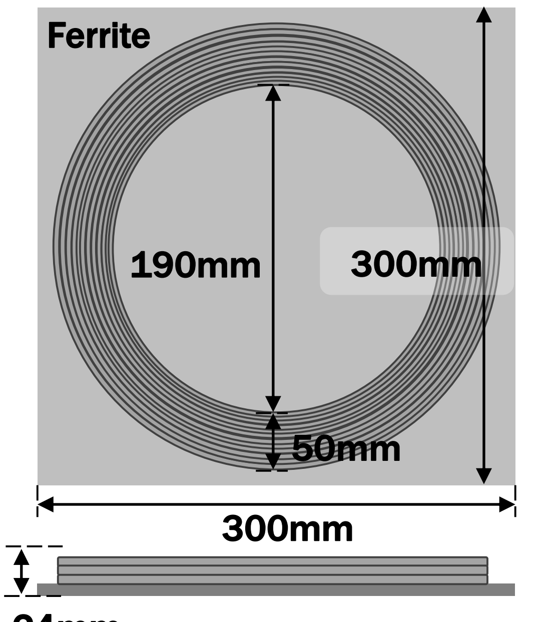
Electromagnetic Field Noise

- **Simulated EMF cancellation by reactive shield**

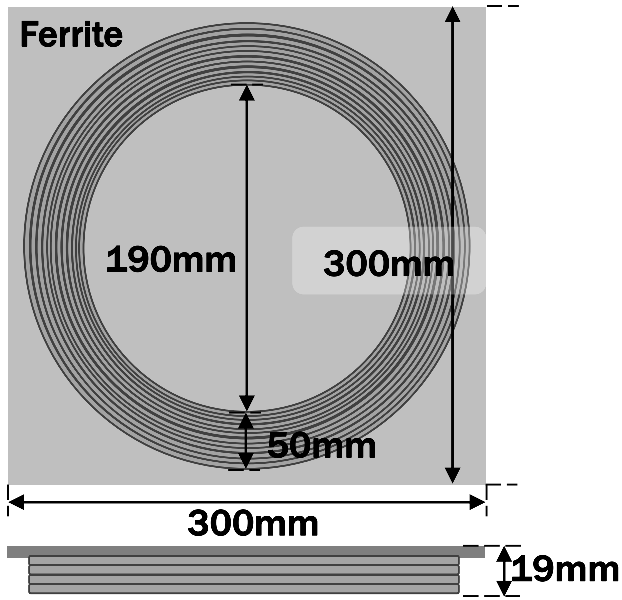


Measurement Setup

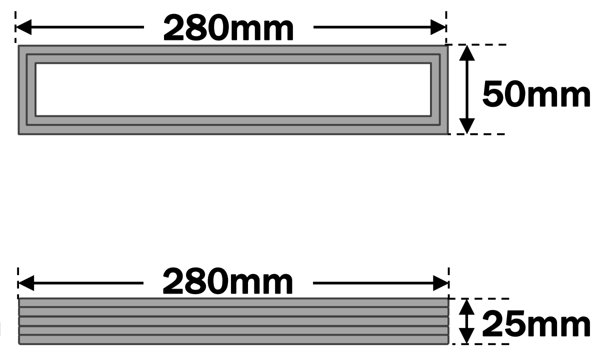
- **Dimensions of source coil, load coil, and reactive coil**



Source coil

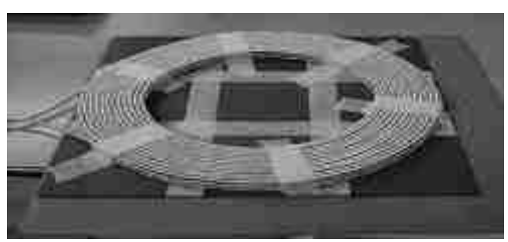


Load coil



Shield coil

Source coil



Load coil

Shield coil

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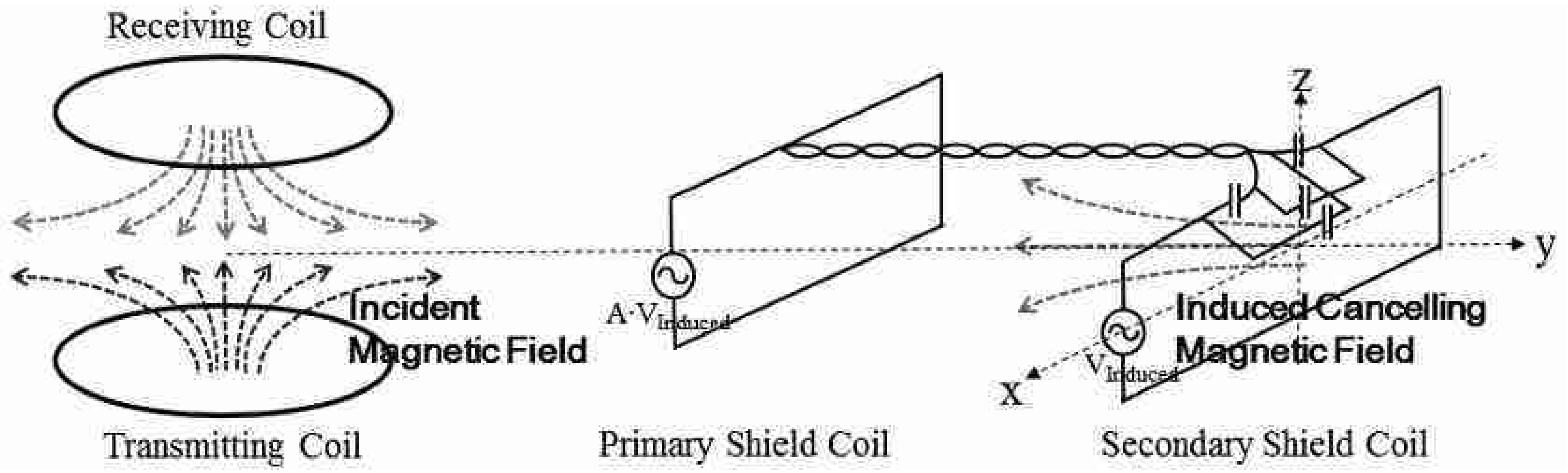
- **The principle of the EMF Cancellation**

S. Kim, H. H. Park, J. Kim, J. Kim, and S. Ahn, "Design and Analysis of a Resonant Reactive Shield for a Wireless Power Electric Vehicle," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 62, No. 4, pp.1057-1066, Apr. 2014.

Reactive Shielding Coil – Type 2

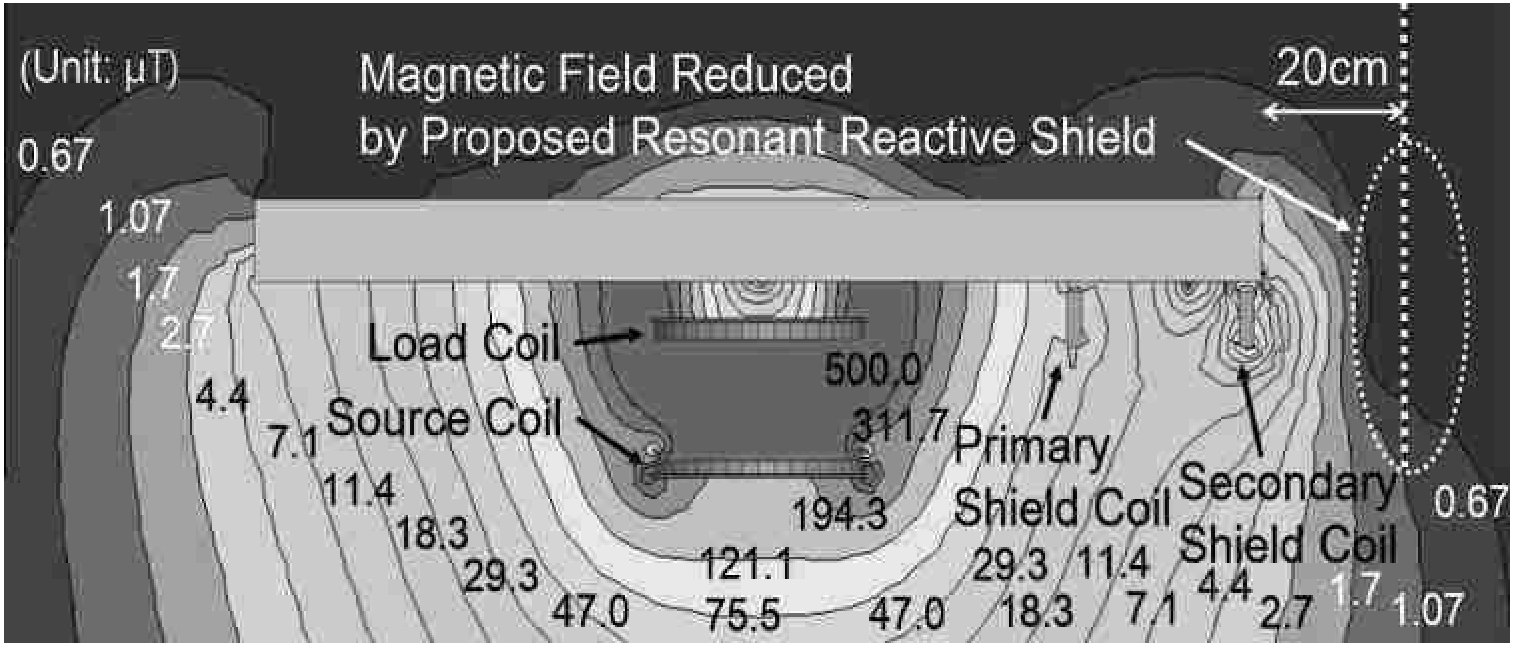
Concept of proposed resonant reactive shield for a wireless power transfer system



- ❑ The resonant reactive shield generates the **induced cancelling magnetic field**.
- ❑ The resonant reactive shield **uses leakage magnetic field** for cancelling magnetic field.
- ❑ The resonant reactive shield **controls the magnitude and phase** of the cancelling magnetic field by **four capacitors**.

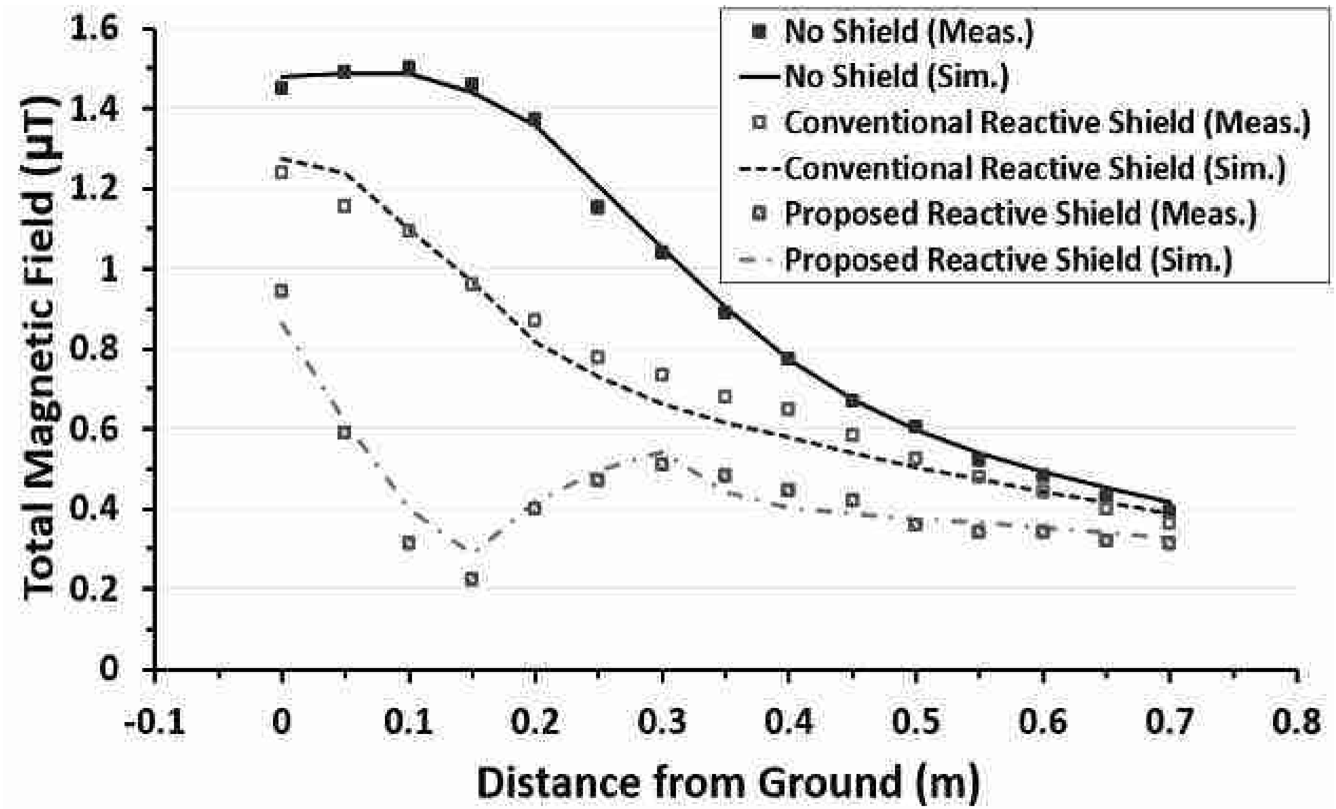
Simulation of the Shielding Performance

Proposed double-reactive shield



❑ Total magnetic field is **significantly reduced** at the observation position by applying the proposed double-reactive shield.

Comparison of the Results



- ❑ The total magnetic field is reduced by **a maximum of 80%** at 0.15 m from ground.

H. Moon, S. Kim, H. H. Park, and S. Ahn, "Design of a Resonant Reactive Shield with Double Coils and a Phase Shifter for Wireless Charging of Electric Vehicles," *IEEE Trans. on Magnetics*, vol. 51, no. 3, Apr. 2015.

Researches on Electromagnetic Interference

Researches on Electromagnetic Field Reduction

❑ EMI Radiation Measurement at 10m

99.01 dBμV/m

55.85 dBμV/m

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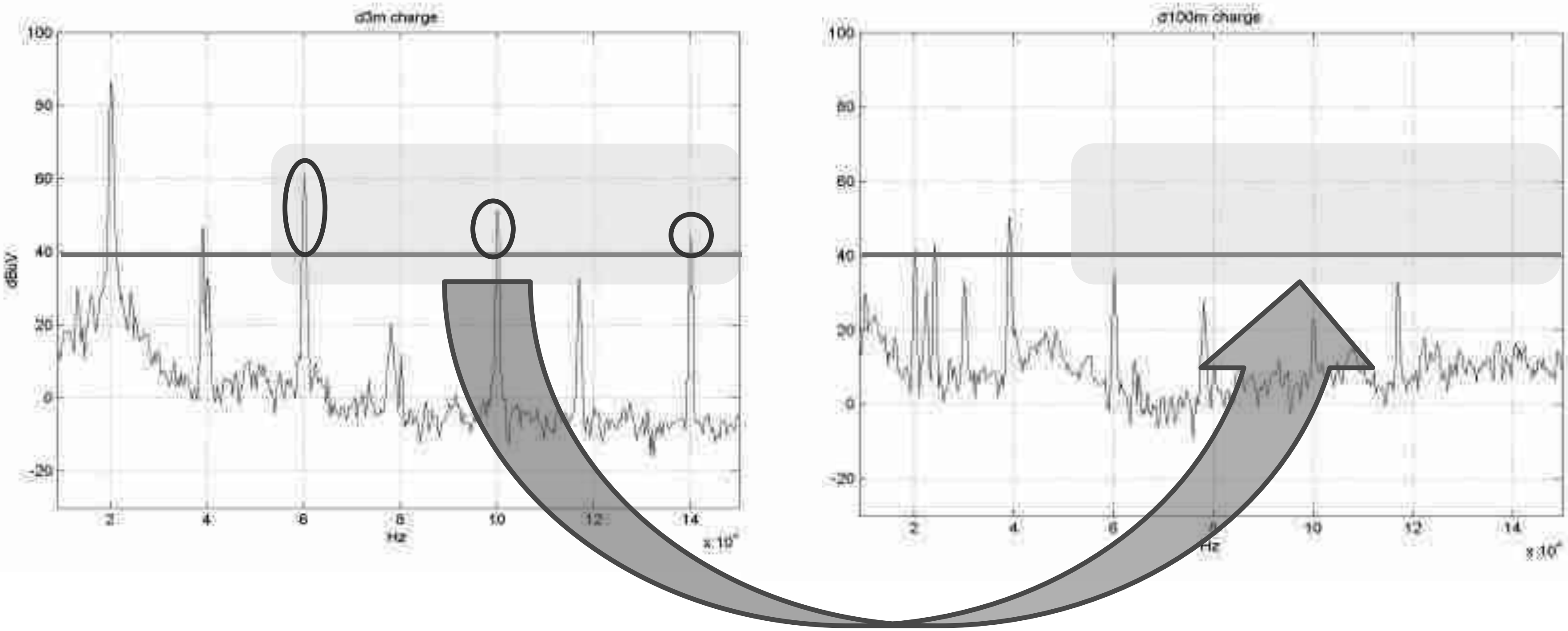
Researches on Electromagnetic Field Reduction

EMI reduction from high power Inverter is required.

➔ EMI filter can reduce harmonic frequency in 150 kHz~10 MHz



Wireless System Construction Guideline (Based on Wireless System Regulation 14-3)

Not only above 150 kHz, but also 60 kHz ~ 140 kHz

Summary

- Wireless power transfer technology is the key of future electric vehicle system.
- Fundamental and applied technologies for wireless charging electric vehicle have been done in Korea since 2009.
- Public buses are commercialized, and railway systems, and passenger cars are being developed.
- Some problems such as electromagnetic issues should be solved for commercialization.

Reference Papers

1. K. Hwang, J. Park, D. Kim, H. H. Park, J. H. Kwon, S. I. Kwak, and S. Ahn, “An Autonomous Coil Alignment System for the Dynamic Wireless Charging of Electric Vehicles to Minimize Lateral Misalignment,” *Energies*, vol. 10, no. 3, Mar. 2017.
2. J. Park, D. Kim, H. H. Park, J. H. Kwon, S. I. Kwak, and S. Ahn, “A Resonant Reactive Shielding for Planar Wireless Power Transfer System in Smart Phone Application,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 59, no. 2, pp. 695 – 703, Jan. 2017.
3. M. Kim, H. Kim, D. Kim, Y. Jeong, H. H. Park, S. Ahn, “A Three-Phase Wireless-Power-Transfer System for Online Electric Vehicles with Reduction of Leakage Magnetic Fields,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 63, No. 11, pp. 3806-3813, Nov. 2015.
4. H. Moon, S. Kim, H. H. Park, and S. Ahn, “Design of a Resonant Reactive Shield with Double Coils and a Phase Shifter for Wireless Charging of Electric Vehicles,” *IEEE Transactions on Magnetics*, vol. 51, no. 3, Apr. 2015
5. T. Batra, E. Schaltz, and S. Ahn, “Effect of Ferrite Addition above the Base Ferrite on the Coupling Factor of Wireless Power Transfer for Vehicle Applications,” *Journal of Applied Physics*, 117(17), 17D517-1, Jan. 2015.
6. S. Kim, H. H. Park, J. Kim, J. Kim, and S. Ahn, "Design and Analysis of a Resonant Reactive Shield for a Wireless Power Electric Vehicle," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 62, No. 4, pp.1057-1066, Apr. 2014.
7. J. Shin, S. Shin, Y. Kim, S. Ahn, S. Lee, G. Jung, B. Song, S. Jeon, and D. H. Cho, "Design and Implementation of a Shaped Magnetic Resonance Based Wireless Power Transfer System for Roadway-Powered Moving Electric Vehicles," *IEEE Transactions on Industrial Electronics*, Vol. 61, No. 3, pp. 1179-1192, Mar. 2014.
8. S. Ahn, C. Hwang, and H. H. Park, “Optimized Shield Design for Reduction of EMF from Wireless Power Transfer Systems” *IEICE Electronics Express*, Vol. 11, No. 2, pp. 1-9, Feb. 2014.
9. Y. Chun, S. Park, J. Kim, J. Kim, H. Kim, J. Kim, N. Kim, and S. Ahn, "Electromagnetic Compatibility of Resonance Coupling Wireless Power Transfer in On-Line Electric Vehicle System,” IE*ICE Transactions on Communications*, Vol. E97-B, No. 2, pp. 416-423, Feb. 2014.
10. J. Kim, J. Kim, S. Kong, H. Kim, I.-S. Suh, N. P. Suh, D.-H. Cho, J. Kim, and S. Ahn, "Coil Design and Shielding Methods for a Magnetic Resonant Wireless Power Transfer System," *Proceedings of the IEEE*, Vol. 101, No. 6, pp. 1332-1342, Jun. 2013.
11. S. Ahn, N. P. Suh, and D.-H. Cho, "Charging Up the Road," *IEEE Spectrum*, pp. 48-54, Apr. 2013.

Thank you