2019 AUT Conference

An Inductively-coupled Wireless Power Transfer Application for Autonomous Underwater Vehicles

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Aim of Presentation

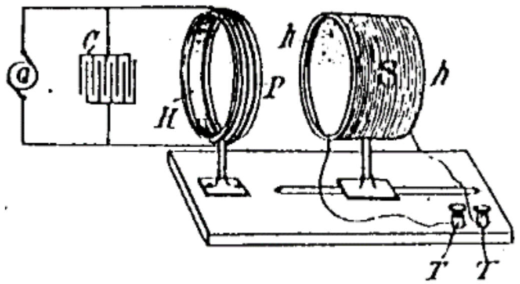
Introduce the trend of Wireless Power Transfer(WPT) System

Deliver the experiment results of prototype

Discuss what parameters are to be considered for underwater WPT

CONTENTS

Classification of Wireless Power Transfer



WPT introduced — By N. Tesla in 1898

Wireless Communication — Advancement of information and communication with microwave technology

Necessity of WPT — Demand for battery-powered devices, EV and sensors

Inductive Coupling

Simple Implementation,
Eddy current loss

Capacitive Coupling

Eddy current free,
High voltage

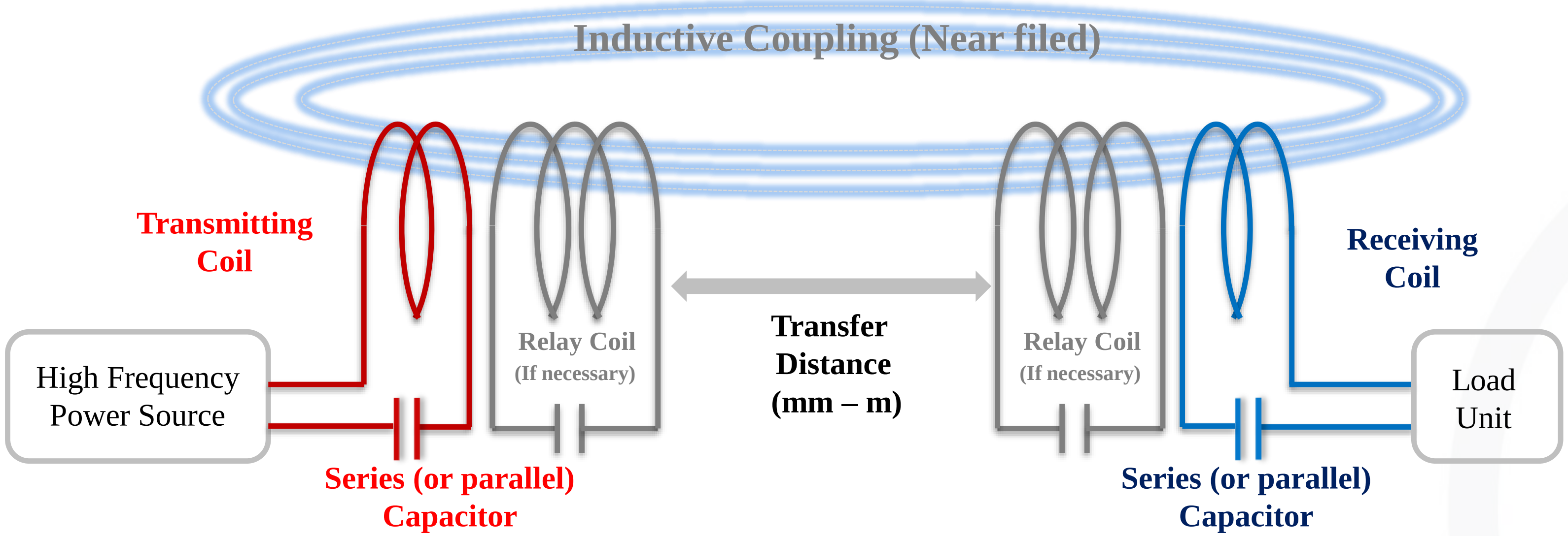
Non-radiation method [Near field]

Microwave WPT

Long transfer distance,
Radiation exposure

Radiation method [Far field]

Inductive power transfer (IPT)



In 1994

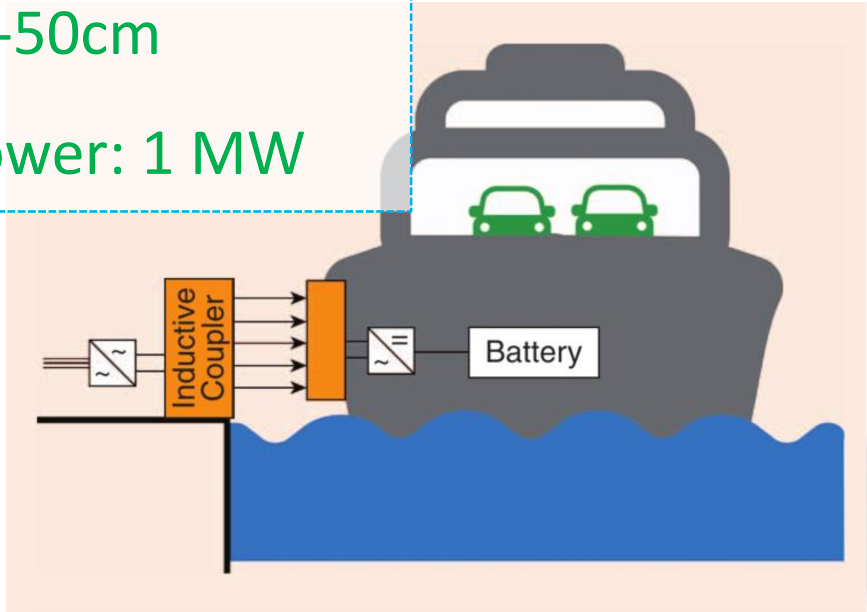
J. Boys (University of Auckland) introduced the 10kHz inductively coupled power transfer (IPT) system to charge the EV's battery.

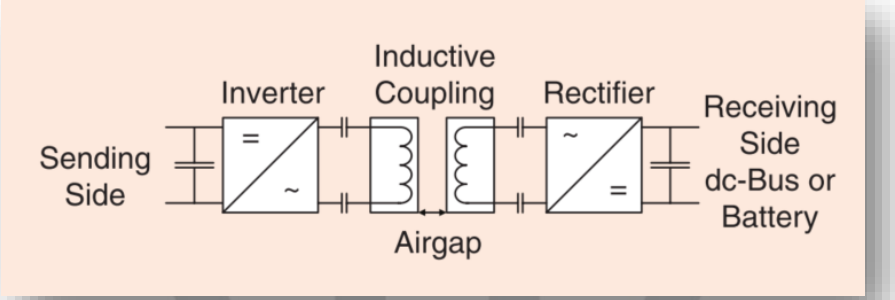
Year	Location	Power	Efficiency	Airgap	Frequency	Application
2007	USA (MIT)	60 W	15%	2 m	9.9 MHz	-
2009	Korea (KAIST)	100 kW	85%	17 cm	20 kHz	EV (Commercial Bus)
2013	N.Z (Uni of Auckland)	2 kW	-	20 cm	20 kHz	EV Battery Charing
2015	Korea Railroad	818 kW	82.7%	5 cm	61.5 kHz	High speed train
2017 (suggested)	Wärtsilä Norway	1 MW	97%	0.1-0.5 m	2-8 kHz	Vessel

Inductive power transfer (IPT)

Gap: 10cm-50cm

Transfer power: 1 MW

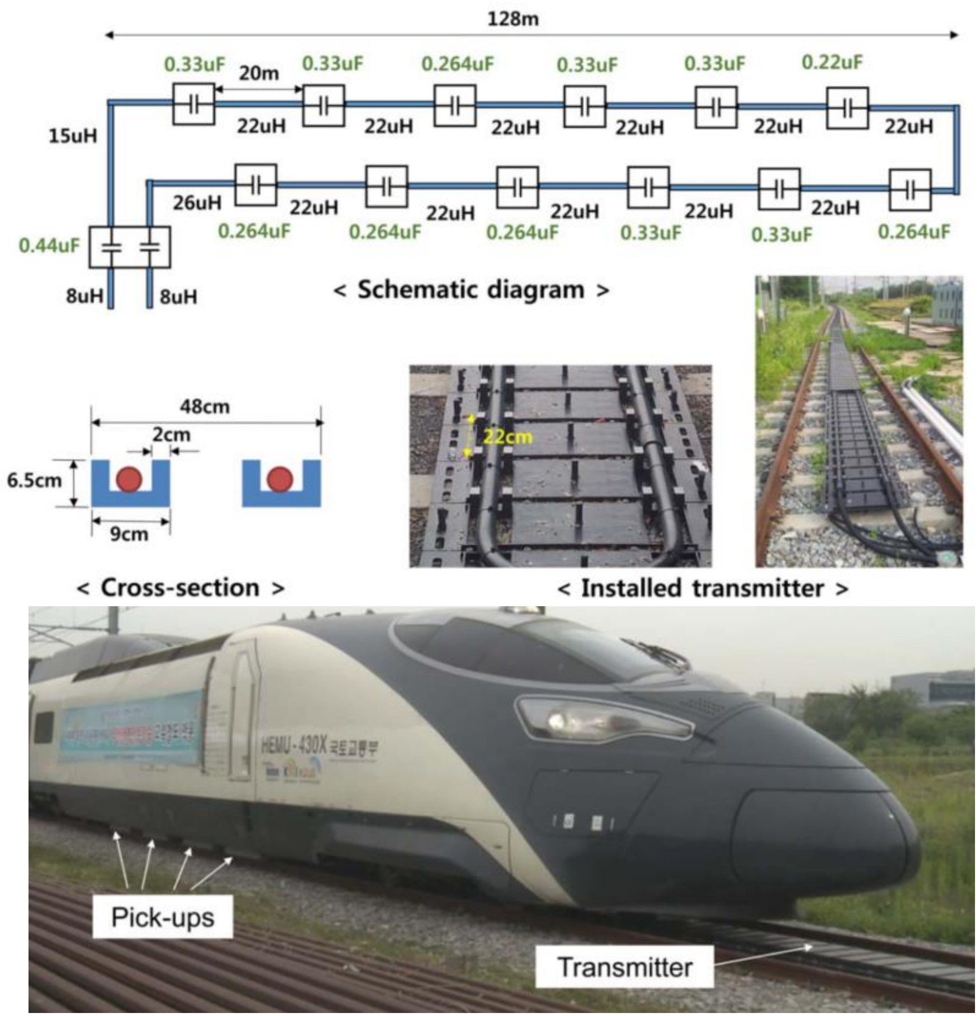




Source

- Guidi, G., Suul, J.A., Jenset, F., and Sorfonn, I., 'Wireless Charging for Ships: High-Power Inductive Charging for Battery Electric and Plug-in Hybrid Vessels', *IEEE Electrification Magazine*, 2017, 5, (3), pp. 22-32.
- Another world's first for Wärtsilä - wireless charging for hybrid coastal ferry successfully tested

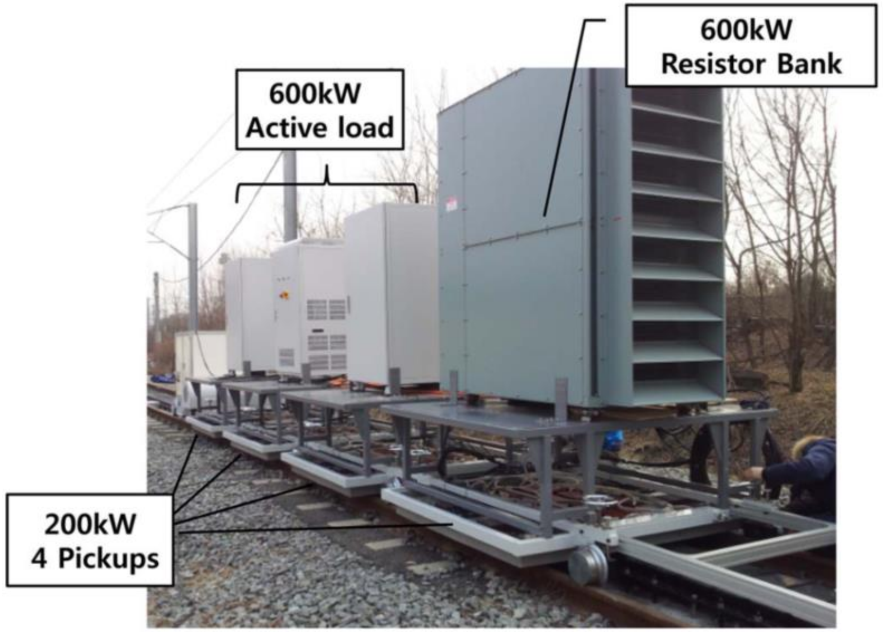
Inductive power transfer (IPT)



Length: 128m,

The rated output current: 300 A

Max. output voltage: 4000V



Source: Kim, J.H., Lee, B.S., Lee, J.H., Lee, S.H., Park, C.B., Jung, S.M., Lee, S.G., Yi, K.P., and Baek, J., 'Development of 1-Mw Inductive Power Transfer System for a High-Speed Train', *IEEE Transactions on Industrial Electronics*, 2015, 62, (10), pp. 6242-6250.

2. Underwater Wireless Power Transfer

Year	Location	Power	Efficiency	Airgap	Frequency	Application
2007	USA	240 W	70%	2 mm	50 kHz	Underwater Vehicle Charging
2010	China	400 W	90%	2 mm	94.3 kHz	4000-m Deep sea
2013	China	45 W	84%	2 mm	167 kHz	Underwater Vehicle Charging
2017	China	10 W	<47% [Z matching]	82 mm	90 kHz	Frequency bifurcation study
2018	USA	1 kW	92.41 %	21 mm	465 kHz	3phase Underwater Vehicle Charging
2019	China	200 W	<90 %	66 mm	60-600 kHz	Underwater Vehicle Charging

2. Underwater Wireless Power Transfer

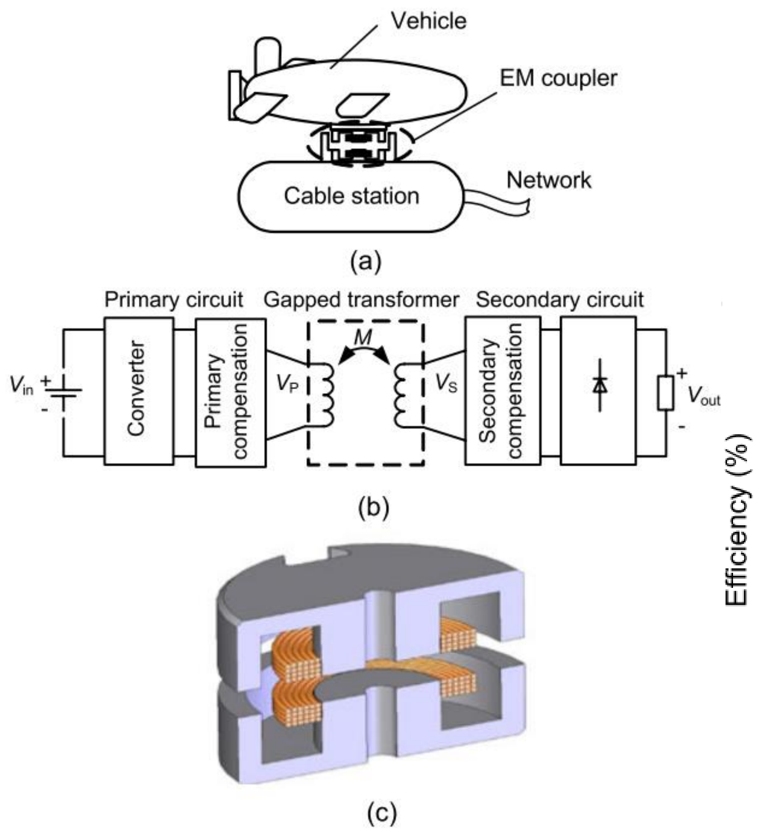
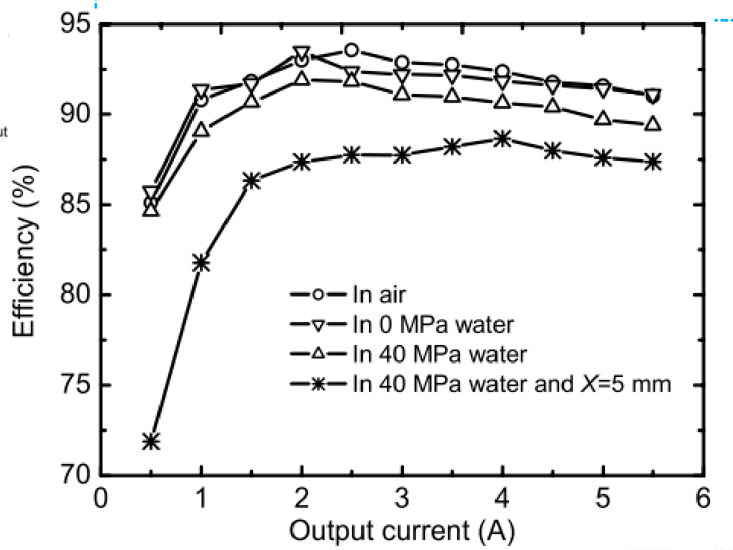


Fig. 1 Illustration of the contactless power transmission (CLPT) system used in underwater applications
(a) Application of a CLPT system; (b) Schematic diagram of the system; (c) Physical structure of the electromagnetic (EM) coupler

Transfer gap: 2 mm

Transfer power: 400 W

Sea water pressure: 40MPa



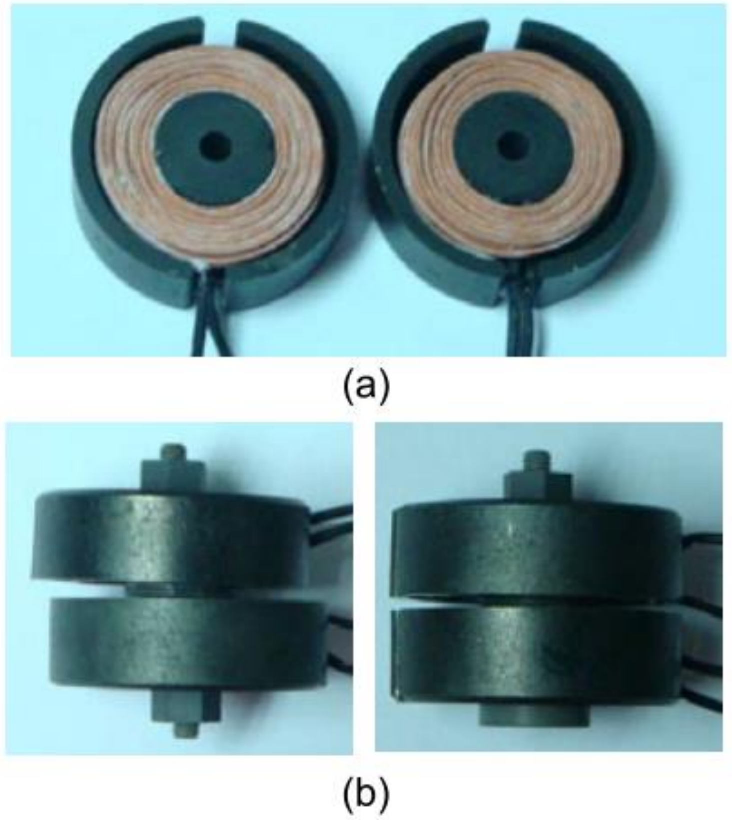
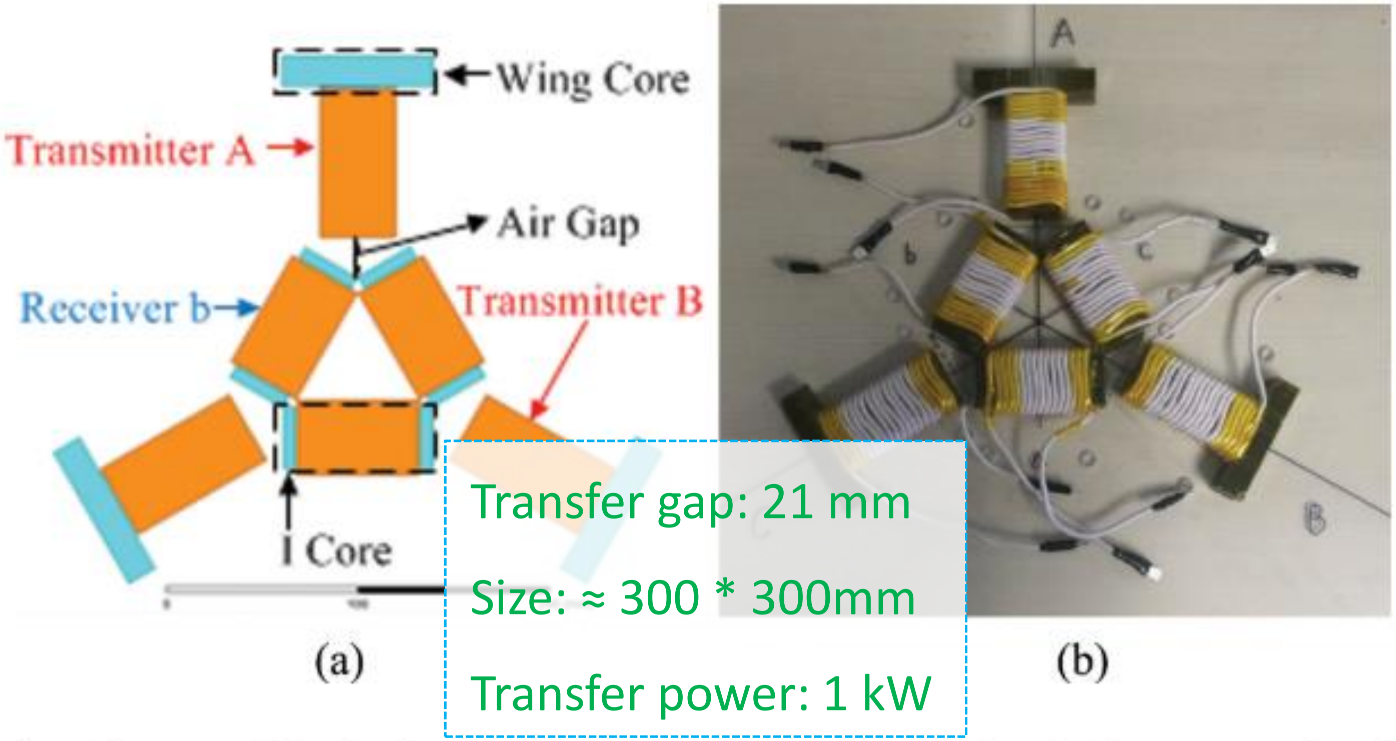


Fig. 7 The 2-mm-gap electromagnetic coupler with P48 pot cores and Litz wire windings
(a) Core halves with windings; (b) Coaxial and noncoaxial alignments of the coupler

Source: Li, Z.-s., et al. (2010). "Design considerations for electromagnetic couplers in contactless power transmission systems for deep-sea ap plications." Computers & Electronics 11(10): 824-834.

2. Underwater Wireless Power Transfer



Transfer gap: 21 mm

Size: ≈ 300 * 300mm

Transfer power: 1 kW

Fig. 12. (a) Simulation and (b) experimental models of the proposed coil structure in Section IV.

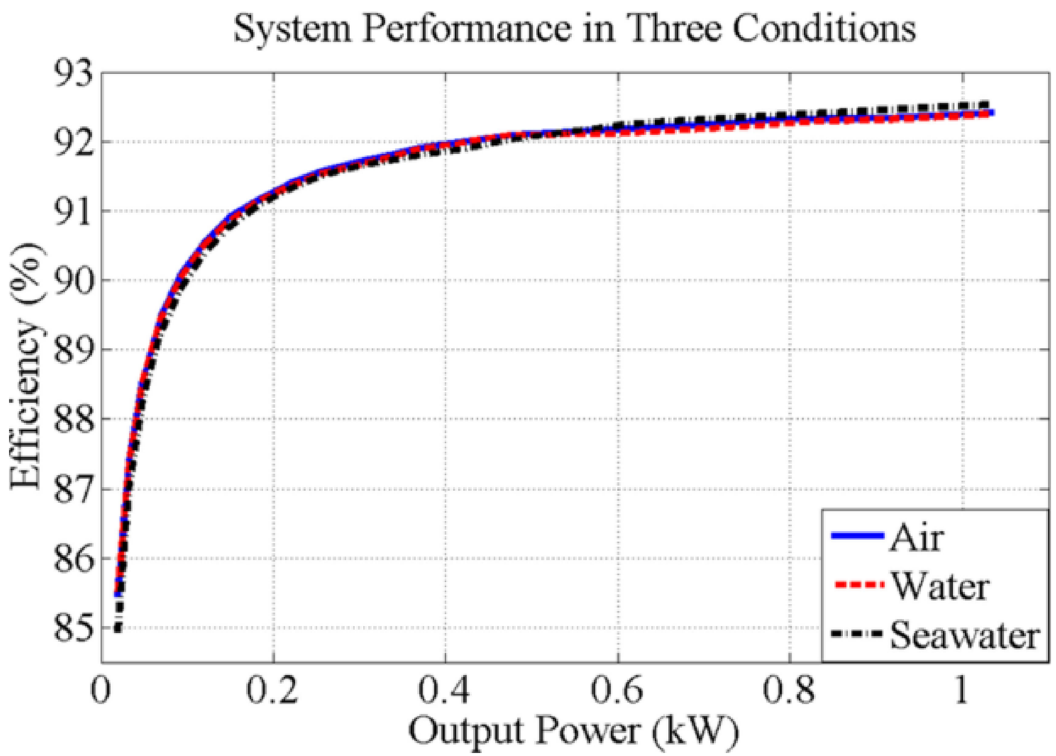


Fig. 17. System performance in three conditions.

Source: Kan, T., et al. (2018). "Design and Analysis of a Three-Phase Wireless Charging System for Lightweight Autonomous Underwater Vehicles." IEEE Trans. Power Electron. 33(8): 6622-6632.

2. Underwater Wireless Power Transfer

Transfer gap: 66 mm

Transfer power: 200 W

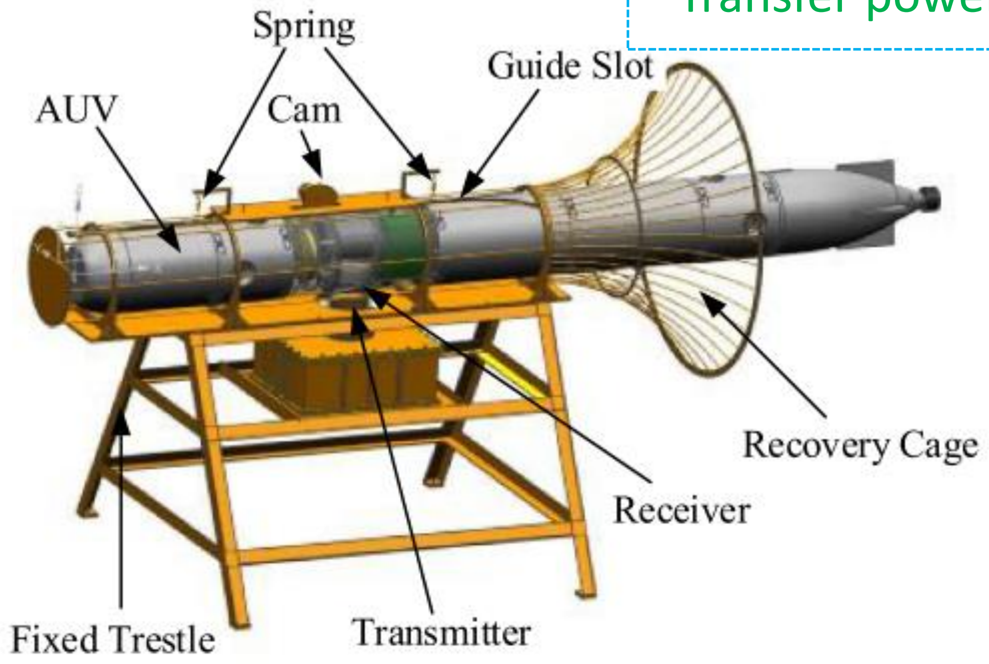


Fig. 2. General overview of the underwater WPT system.

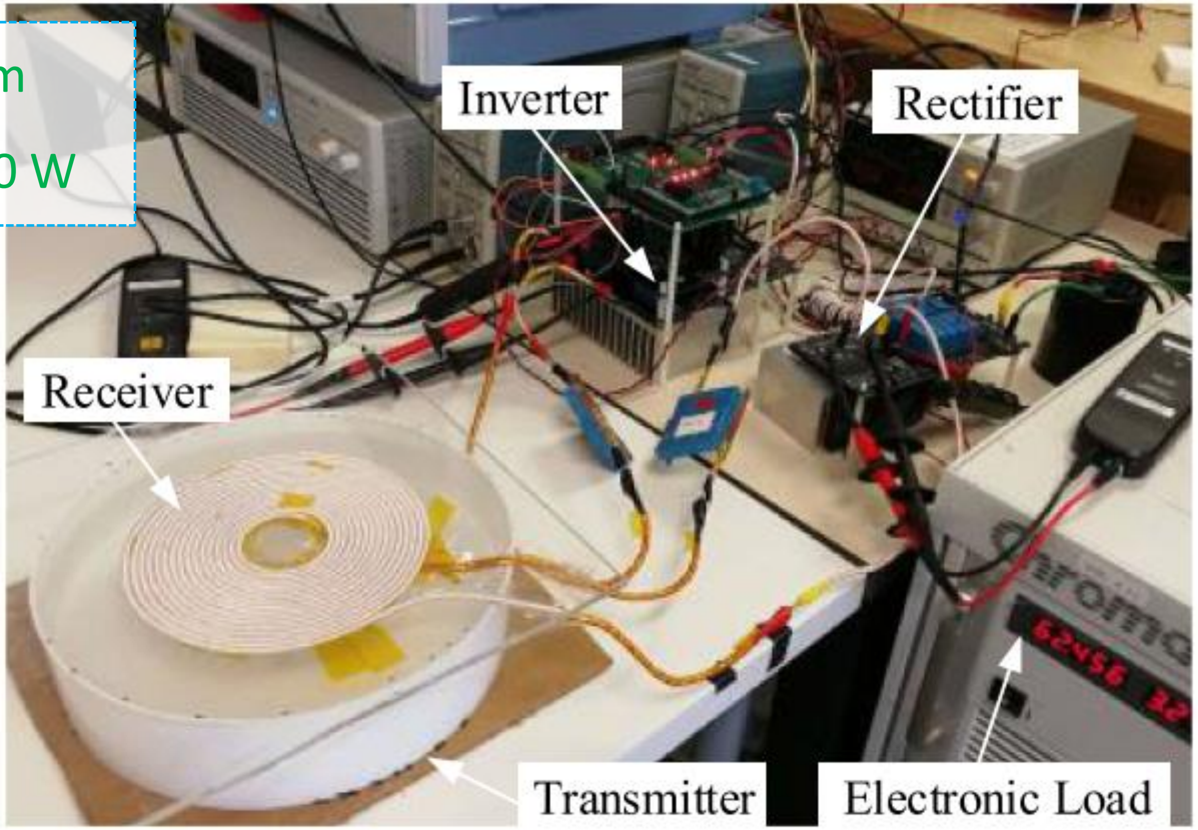
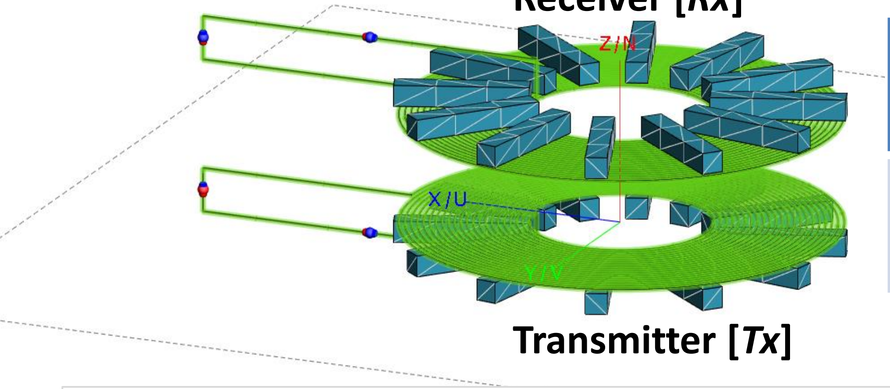


Fig. 6. Experimental prototype.

Source: Yan, Z., et al. (2019). "Frequency Optimization of a Loosely Coupled Underwater Wireless Power Transfer System Considering Eddy Current Loss." IEEE Transactions on Industrial Electronics 66(5): 3468-3476.

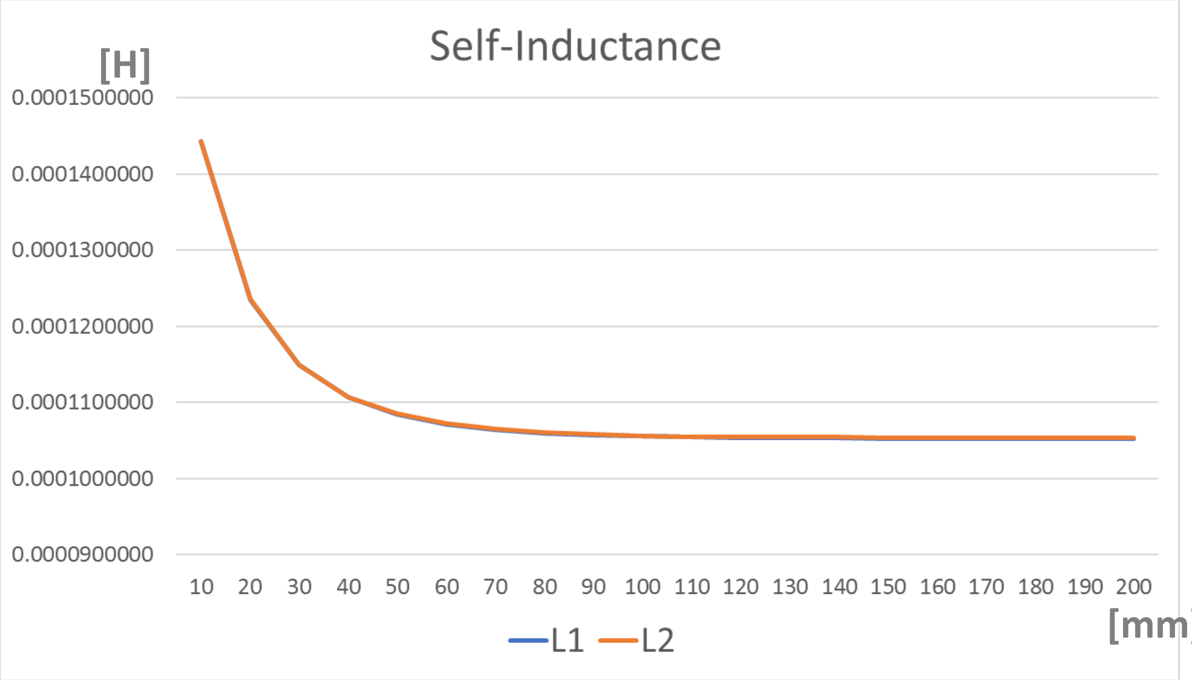
WPT Coil Design

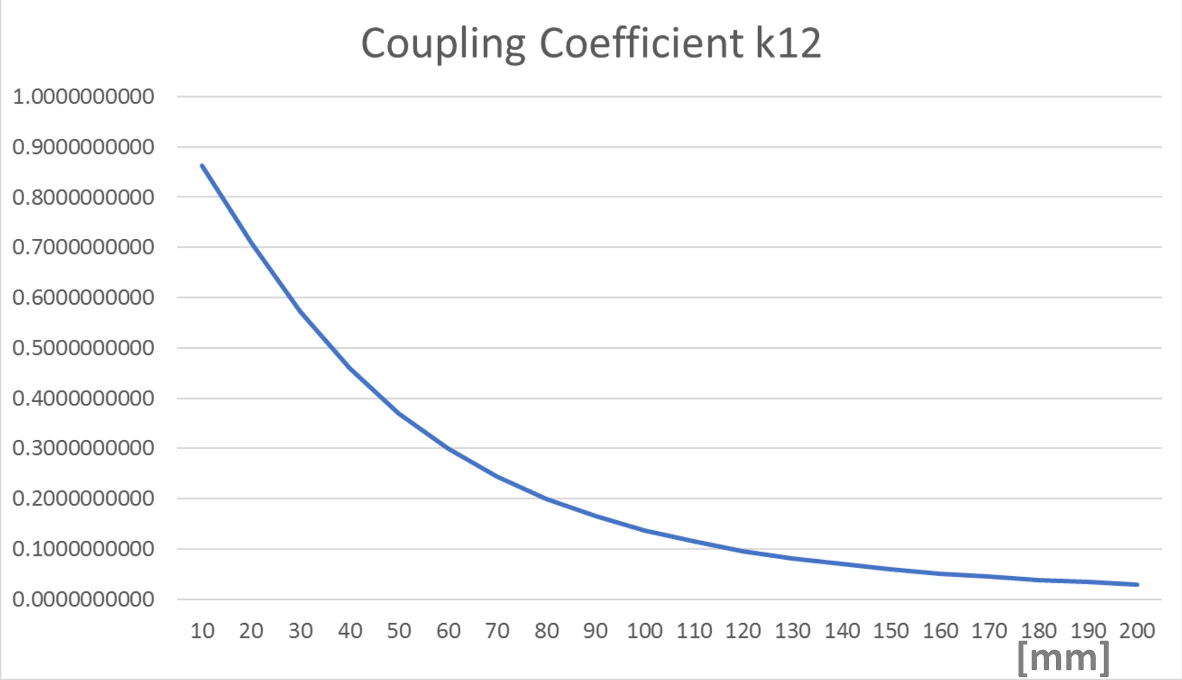
Receiver [*Rx*]



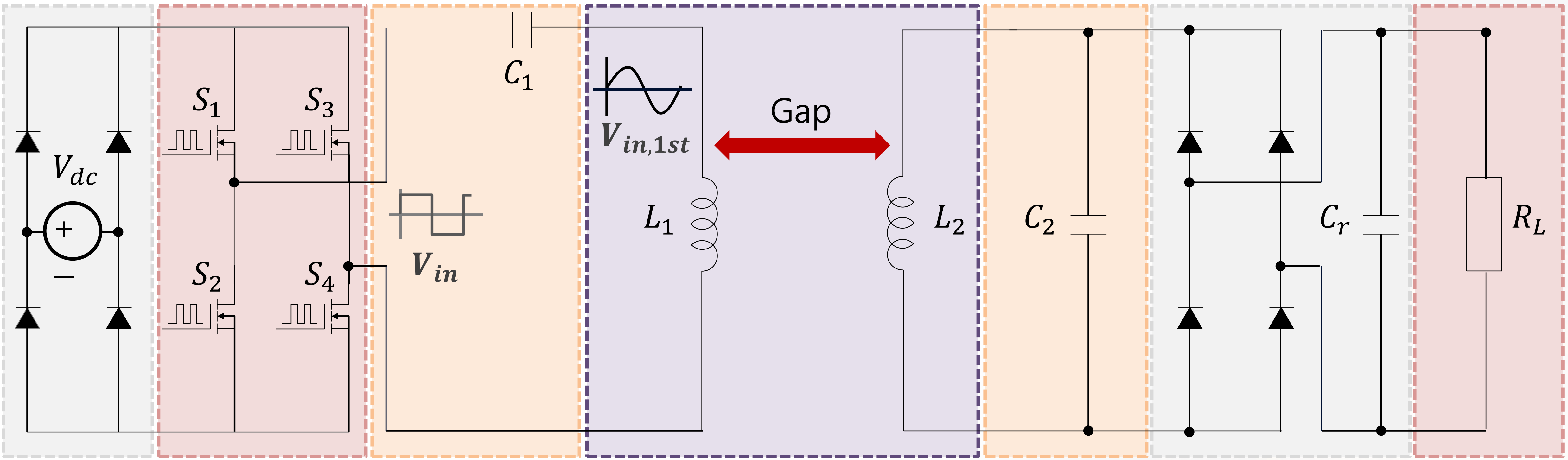
Transmitter [*Tx*]

Wire Material	Wire Radius	Wire Insulation	Loop Shape	Loop Radius	Loop Turns	Ferrite Rods	Ferrite Rod μ
Copper	0.565mm	PVC 0.8mm	Spiral	40mm (in) 100mm (out)	22	12 (per 30˚)	2000





Circuit of WPT Application



DC Source

DC-AC Inverter
- Switching loss
  (soft switching ZVS, ZCS)
- Types of converter
- Protection

Compensating Capacitor

Coils (Inductor) & Magnetic Coupling
- Compensation topologies
  (SS, SP, PS, PP, LCL and etc)
- E.M.I & Safety
- Wire loss (Litz coil)

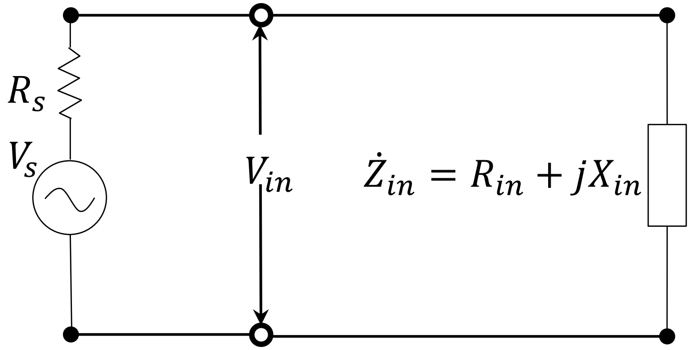
Compensating Capacitor

AC-DC Rectifier
- Constant voltage
  or current
- Regulation

Load
- Battery
  modelling

3. Design WPT for AUT

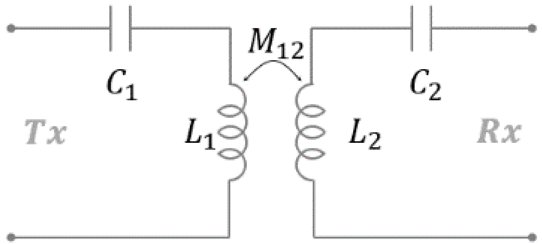
Compensation and Impedance



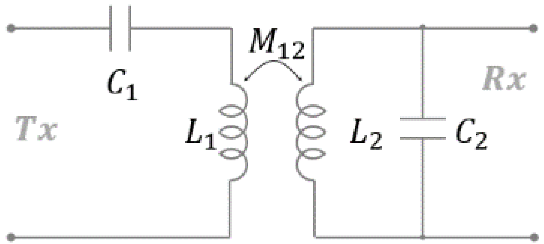
For resonance of WPT circuit: $jX_{in} = 0$ [Zero imaginary (Reactive) element]

For maximum power transfer: $R_s = Z_{in}$

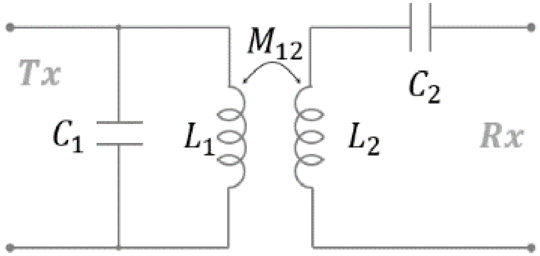
For maximum power efficiency: R_s=0 and high Z_{in}



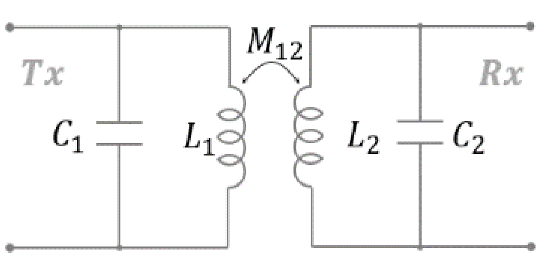
Series-Series



Series-Parallel



Parallel-Series



Parallel-Parallel

Series-Series

$$Z_{in} = \frac{\omega_o^2 M_{12}^2}{R_L}$$

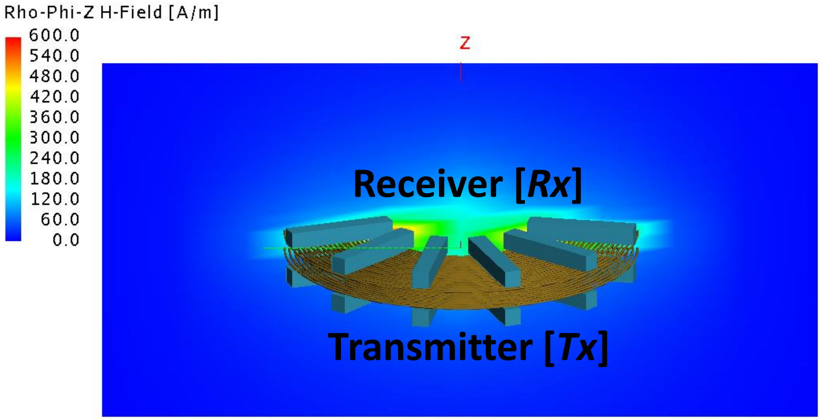
$R_L \uparrow$	$Z_{in} \downarrow$
$\omega \uparrow$	$Z_{in} \uparrow\uparrow$
$M_{12} \downarrow$	$Z_{in} \downarrow\downarrow$

Series-Parallel

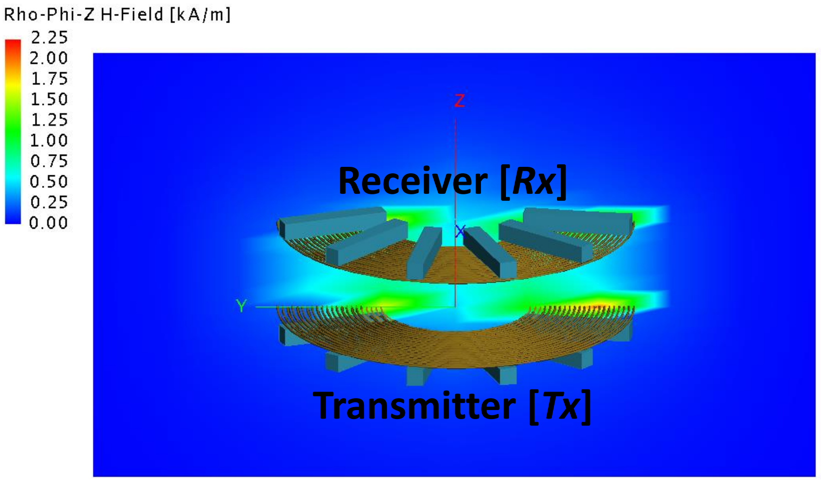
$$Z_{in} = R_L \frac{M_{12}^2}{L_2^2}$$

$R_L \uparrow$	$Z_{in} \uparrow$
$L_2 \downarrow$	$Z_{in} \uparrow\uparrow$
$M_{12} \downarrow$	$Z_{in} \downarrow\downarrow$

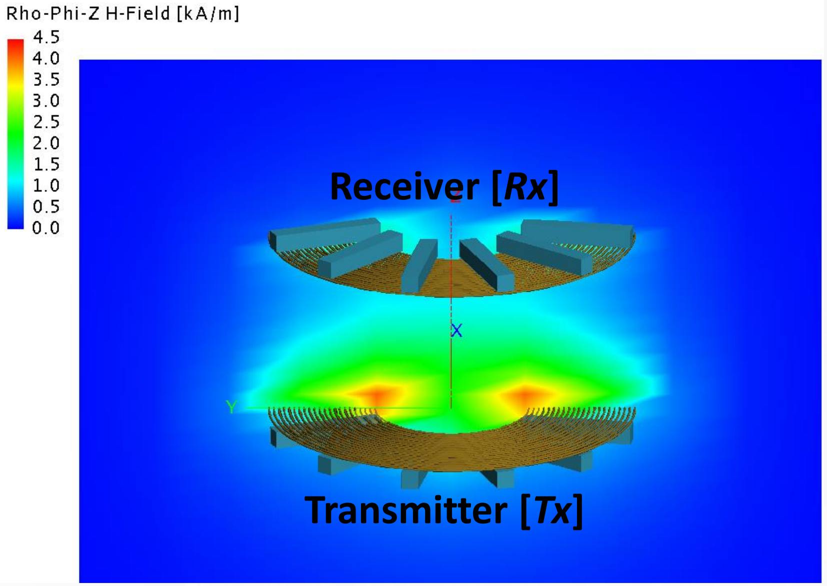
Magnetic coupling over distance



10 mm



50 mm



100 mm

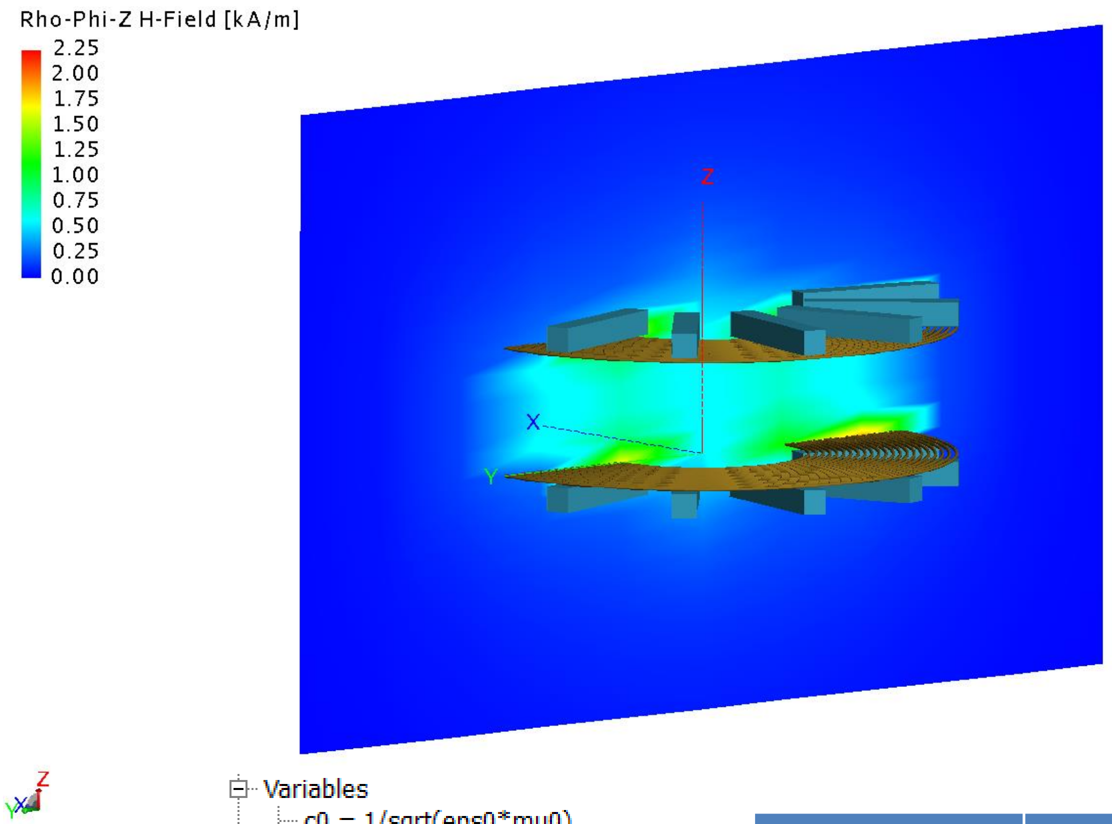
TABLE I
REFERENCE PARAMETERS FOR SUBMARINE EM PROPAGATION

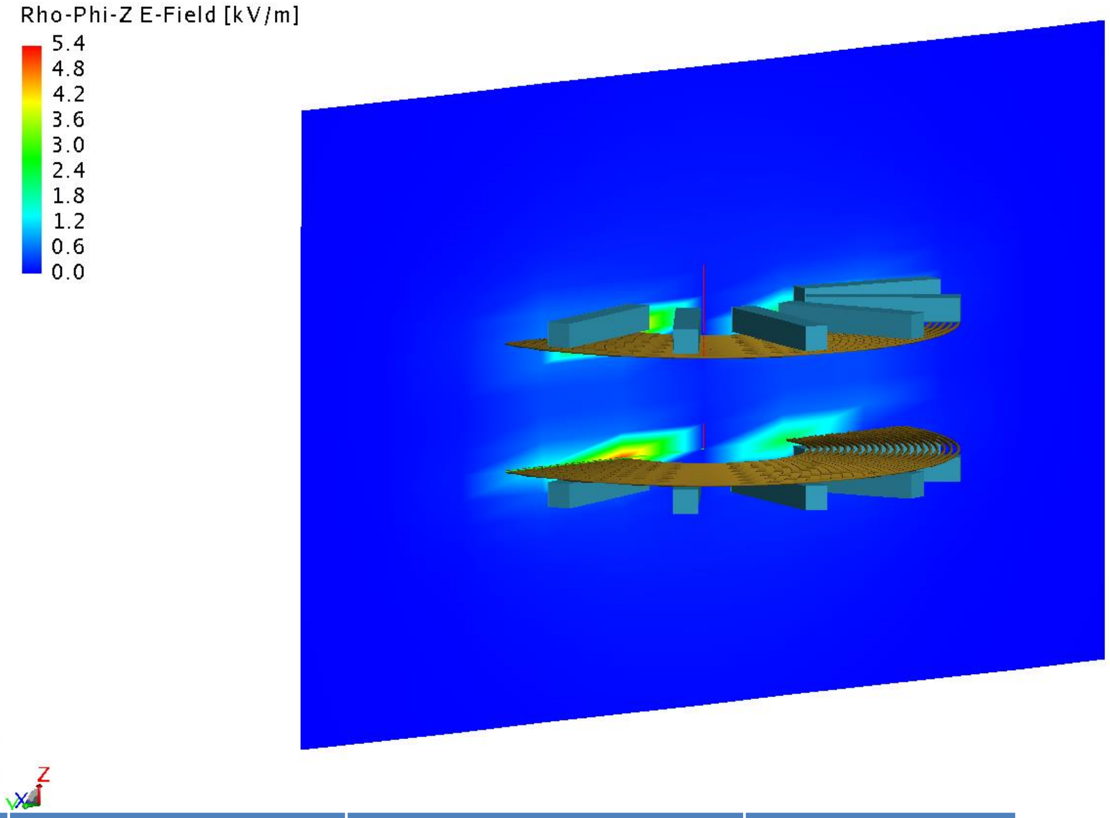
Symbol	Quantity	Units	Sea Water
σ	conductivity	S/m	4
μ_0	permeability	H/m	$4\pi \cdot 10^{-7}$
μ_r	relative seawater permeability		1
ε_0	permittivity	F/m	$8.854 \cdot 10^{-12}$
ε_r	relative seawater permittivity		81

Uribe, C. and W. Grote (2009). Radio Communication Model for Underwater WSN. 2009 3rd International Conference on New Technologies, Mobility and Security.

3. Design WPT for AUT

Electromagnetic field study



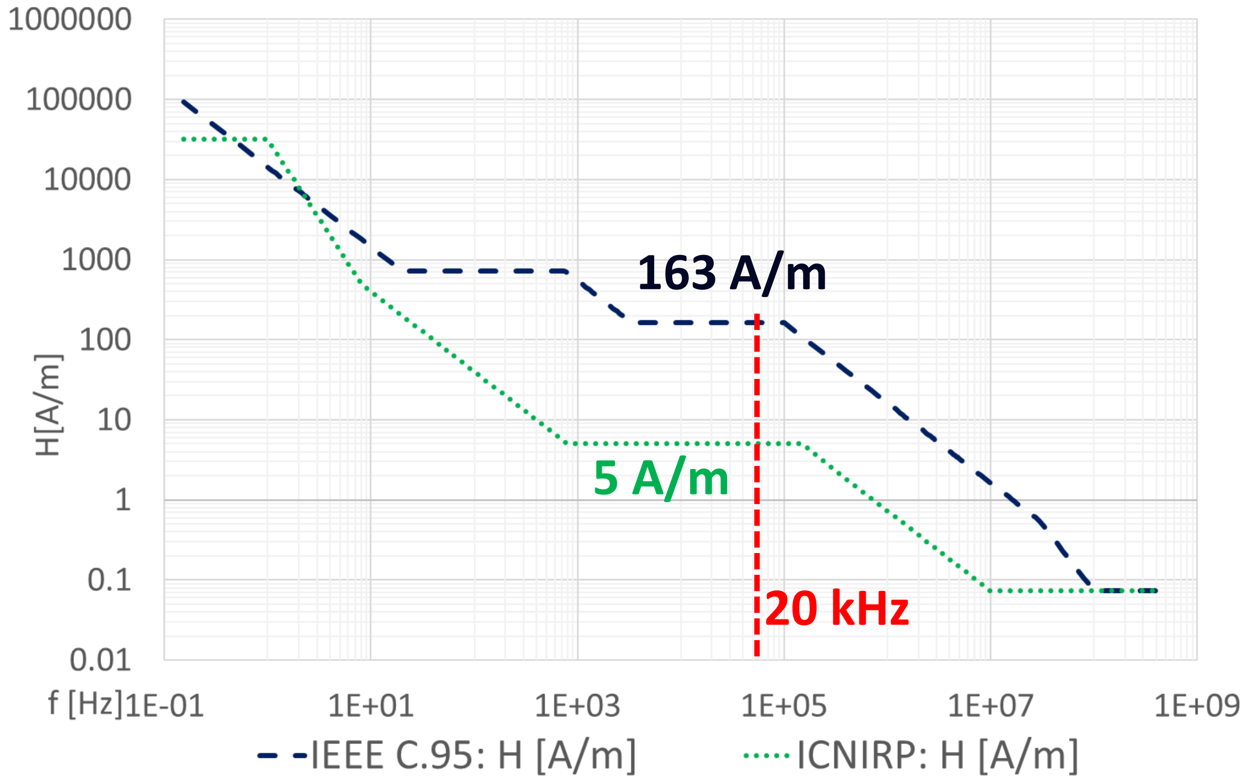


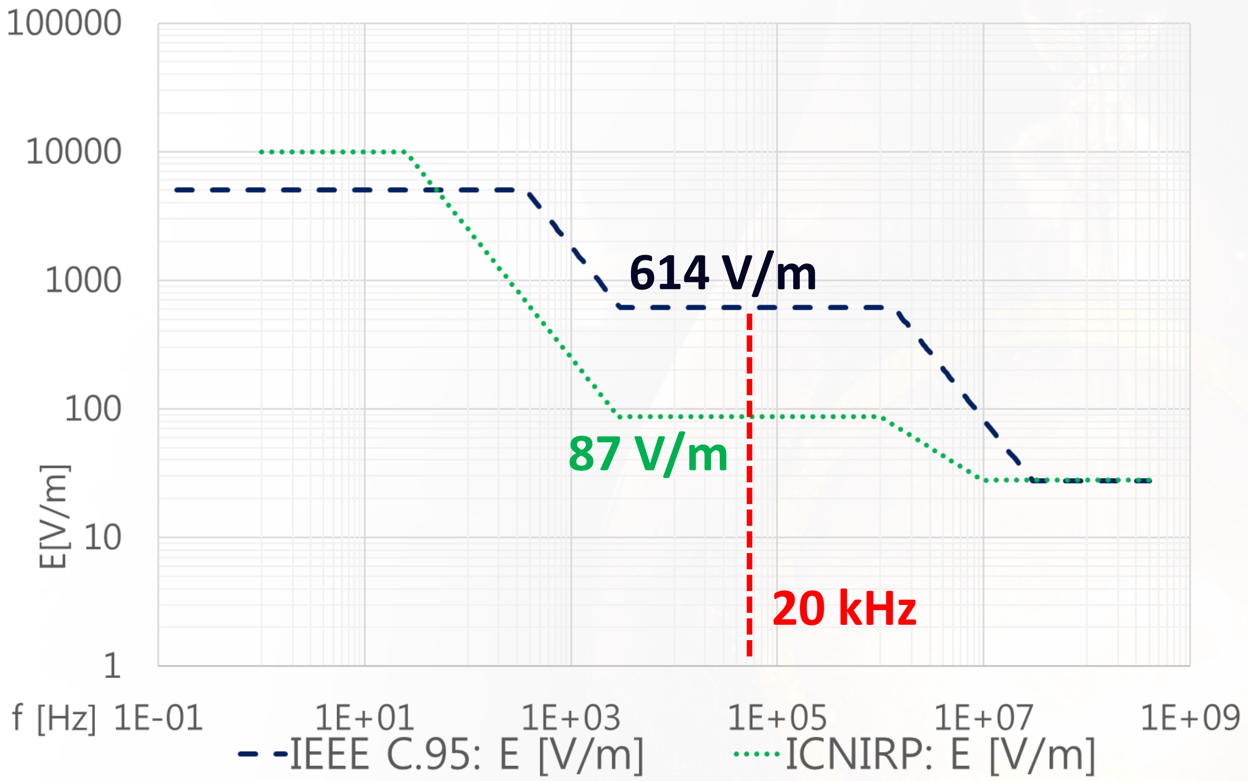
Variables
- c0 = 1/sqrt(eps0*mu0)
- dist = 50
- eps0 = 8.85418781761e-12
- in_radius = 40
- mu0 = pi*4e-7
- out_radius = 100
- pi = 3.14159265358979323846
- turns = 22
- wire_r = 0.565
- zf0 = sqrt(mu0/eps0)

Distance	Inductance L1	Parasitic Wire Resistance	Coupling Coefficient k12	Frequency
50 mm	104 uH	0.3 Ω	0.3703	20 kHz

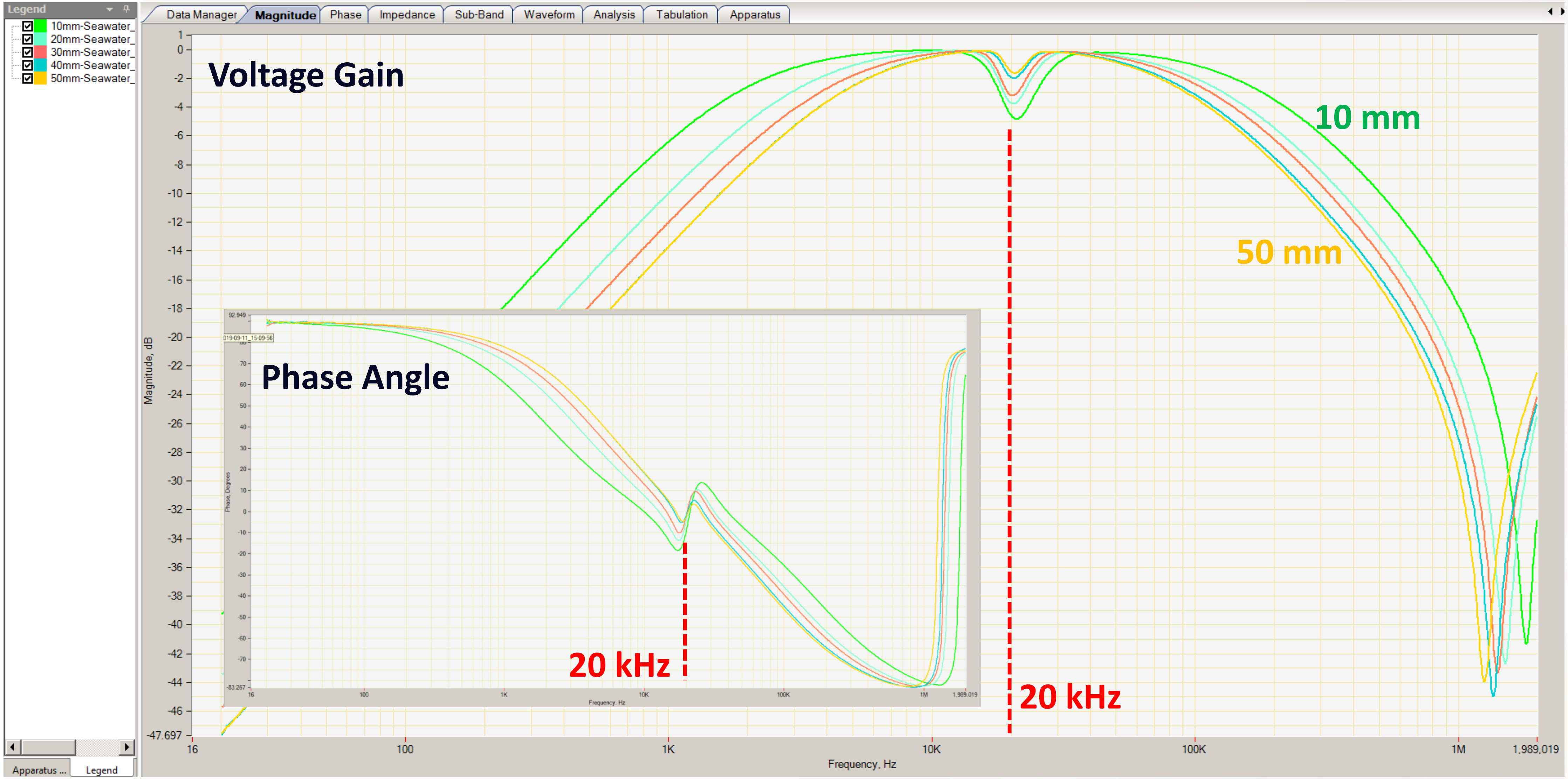
3. Design WPT for AUT

Electric and Magnetic Field Guideline



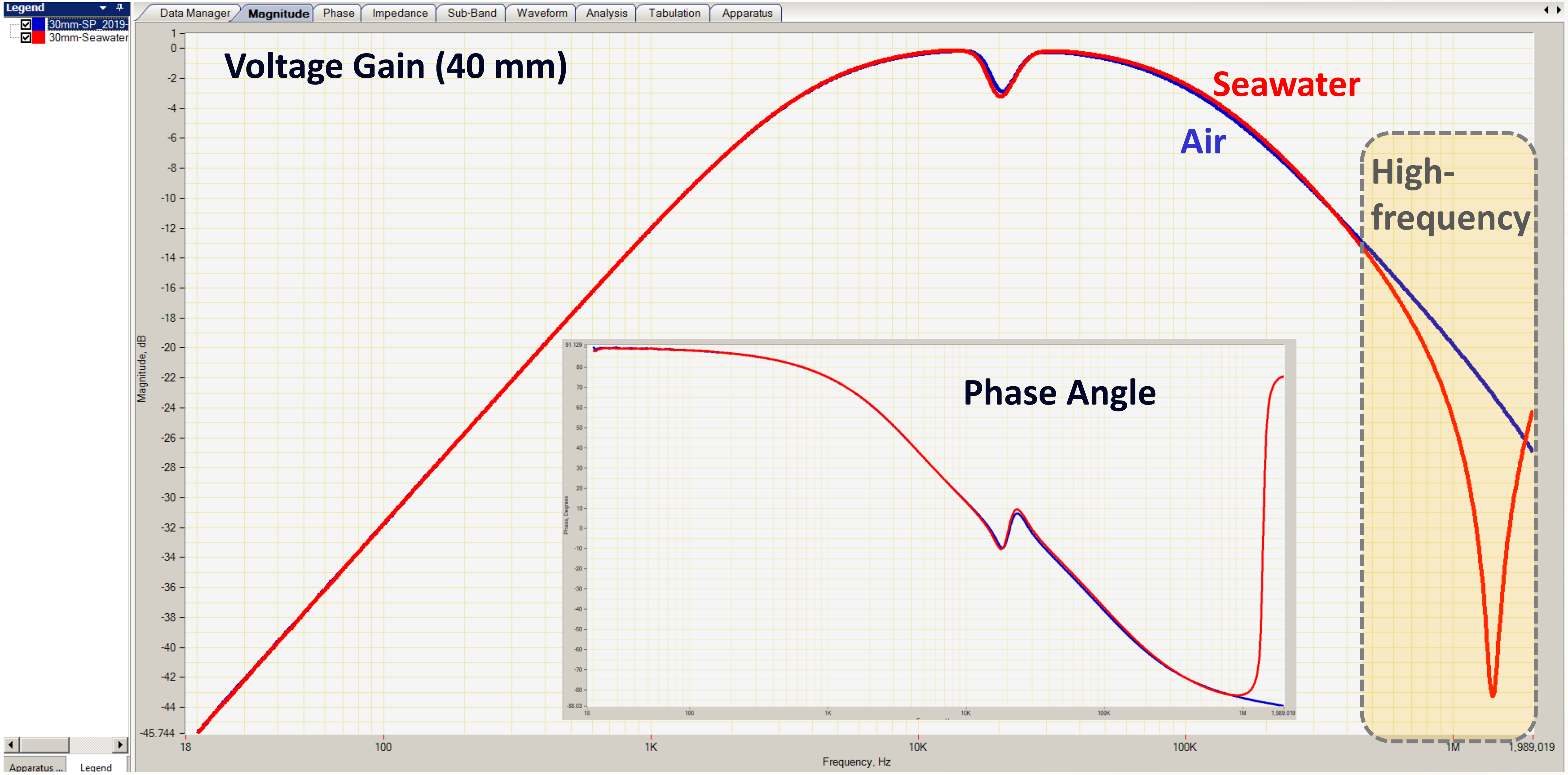


Frequency Response Analysis

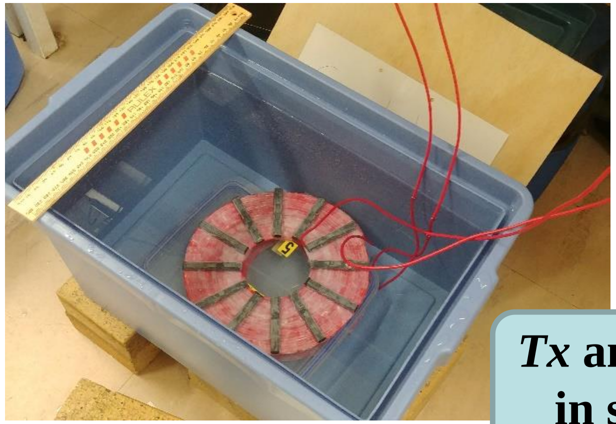


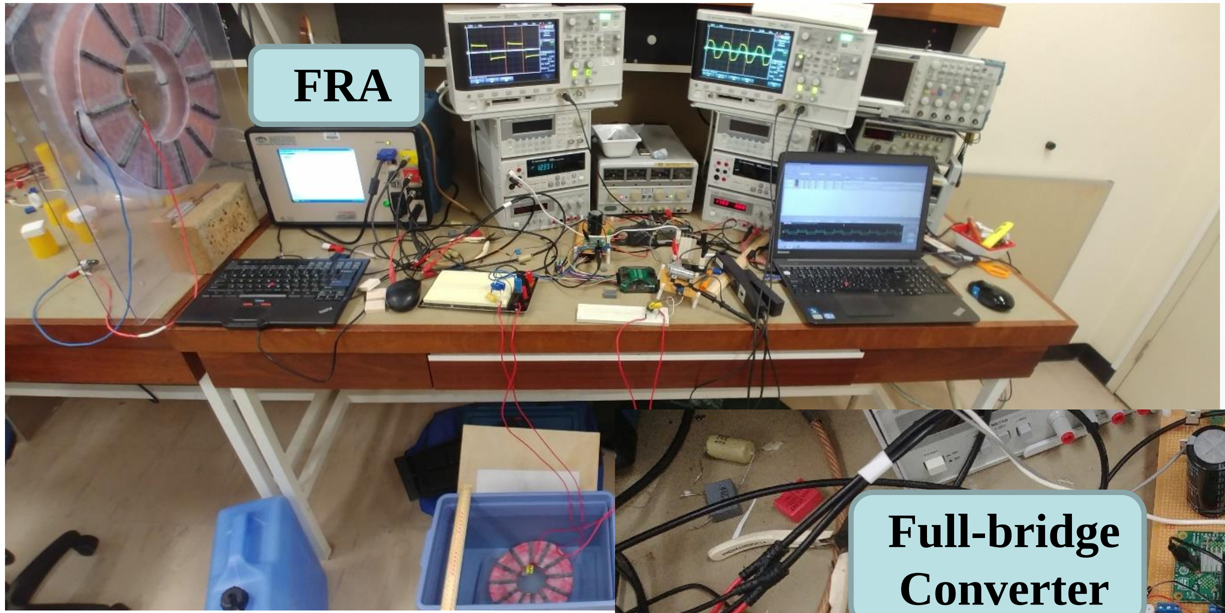
3. Design WPT for AUT

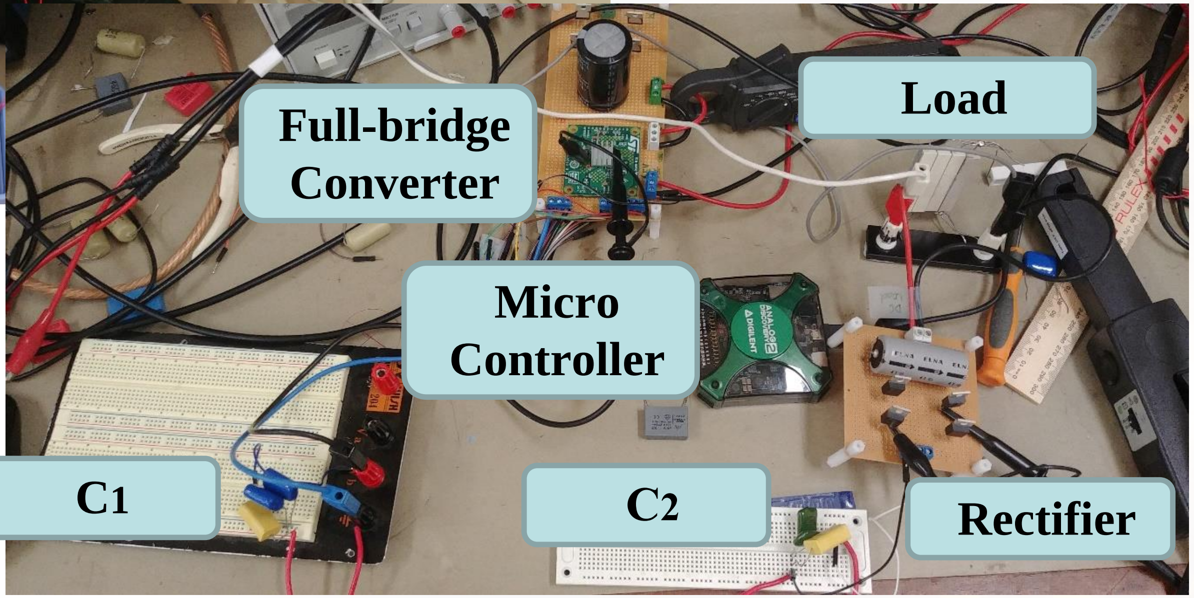
Frequency Response Analysis



Experiment Setup



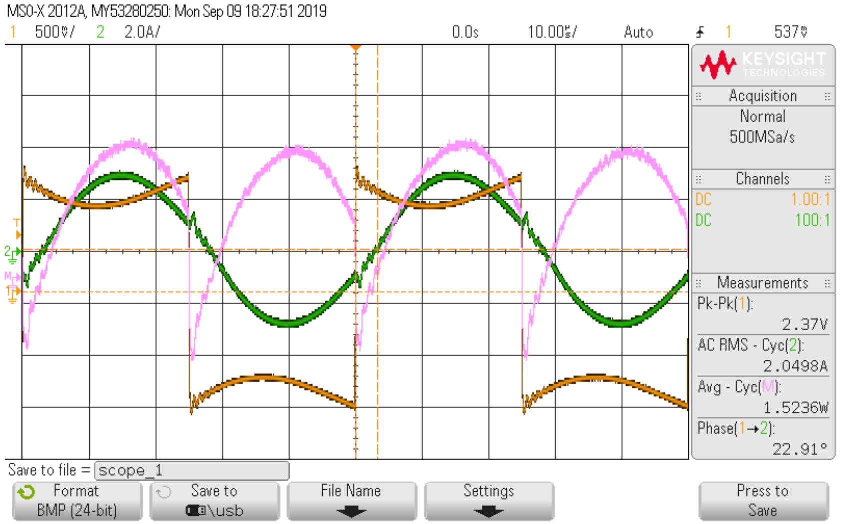




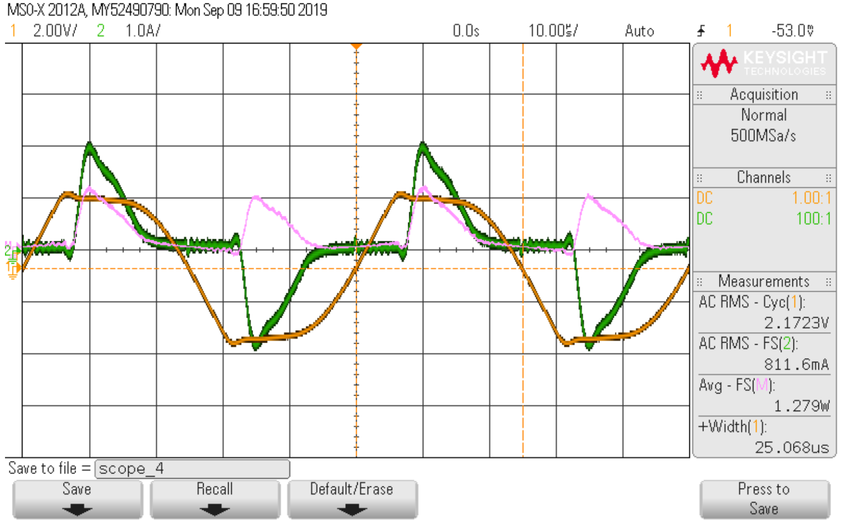
Transfer Power Measurement

Air 50 [mm]

Tx
15.24 W

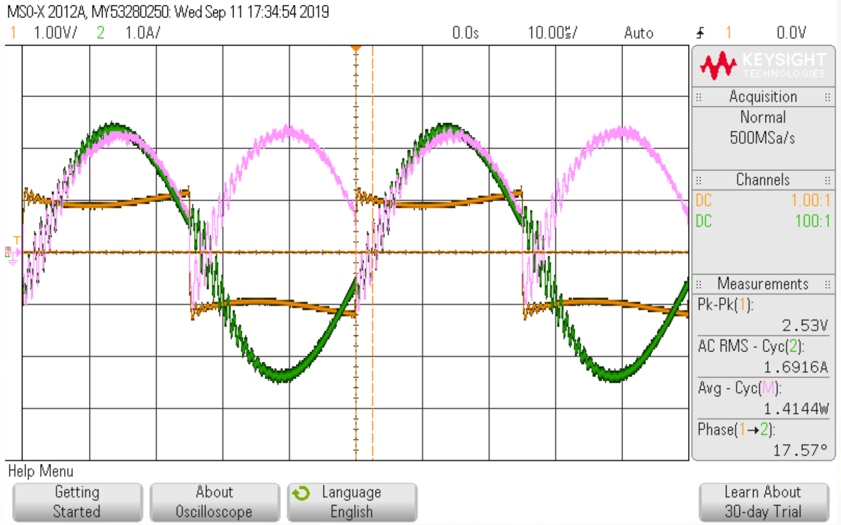


Rx
12.79 W

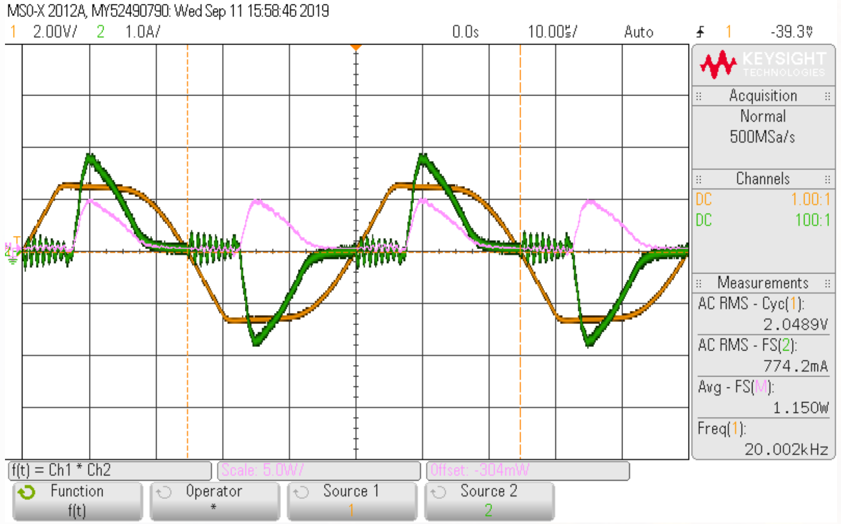


Seawater 50 [mm]

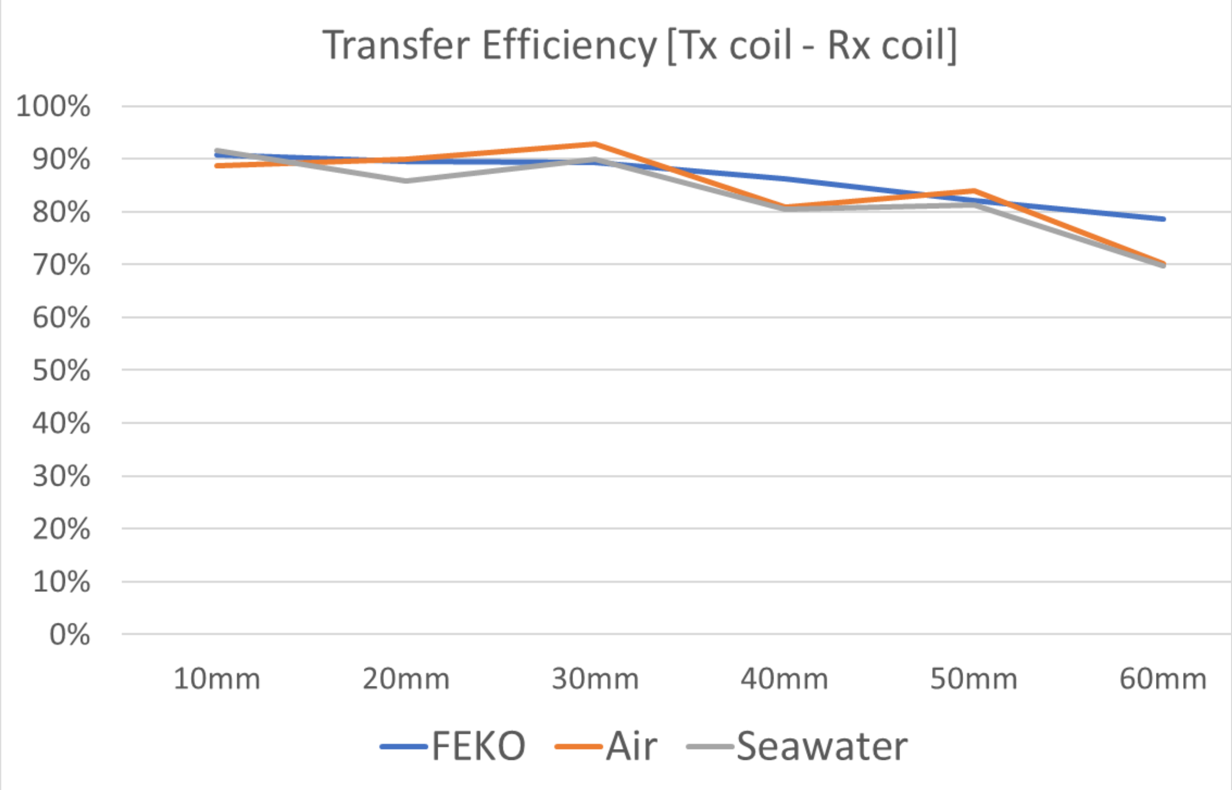
Tx
14.41 W

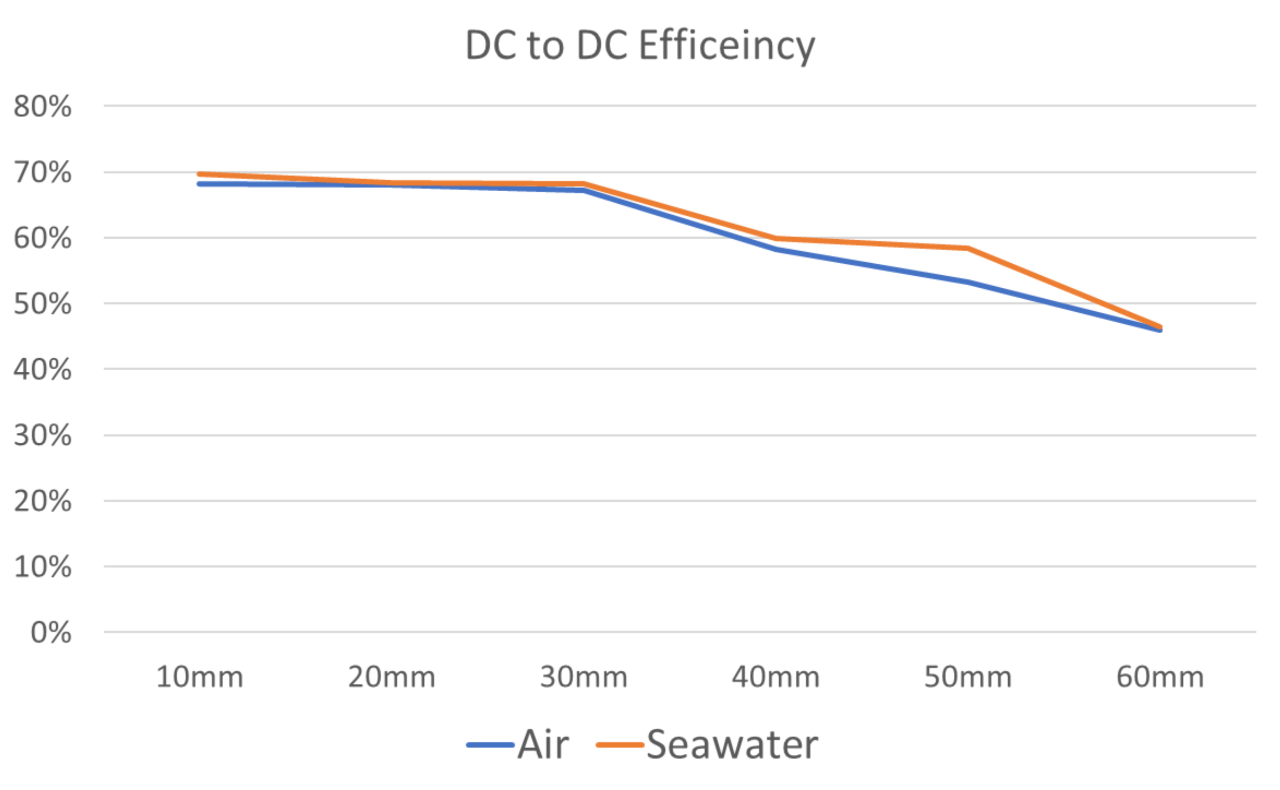


Rx
11.50 W



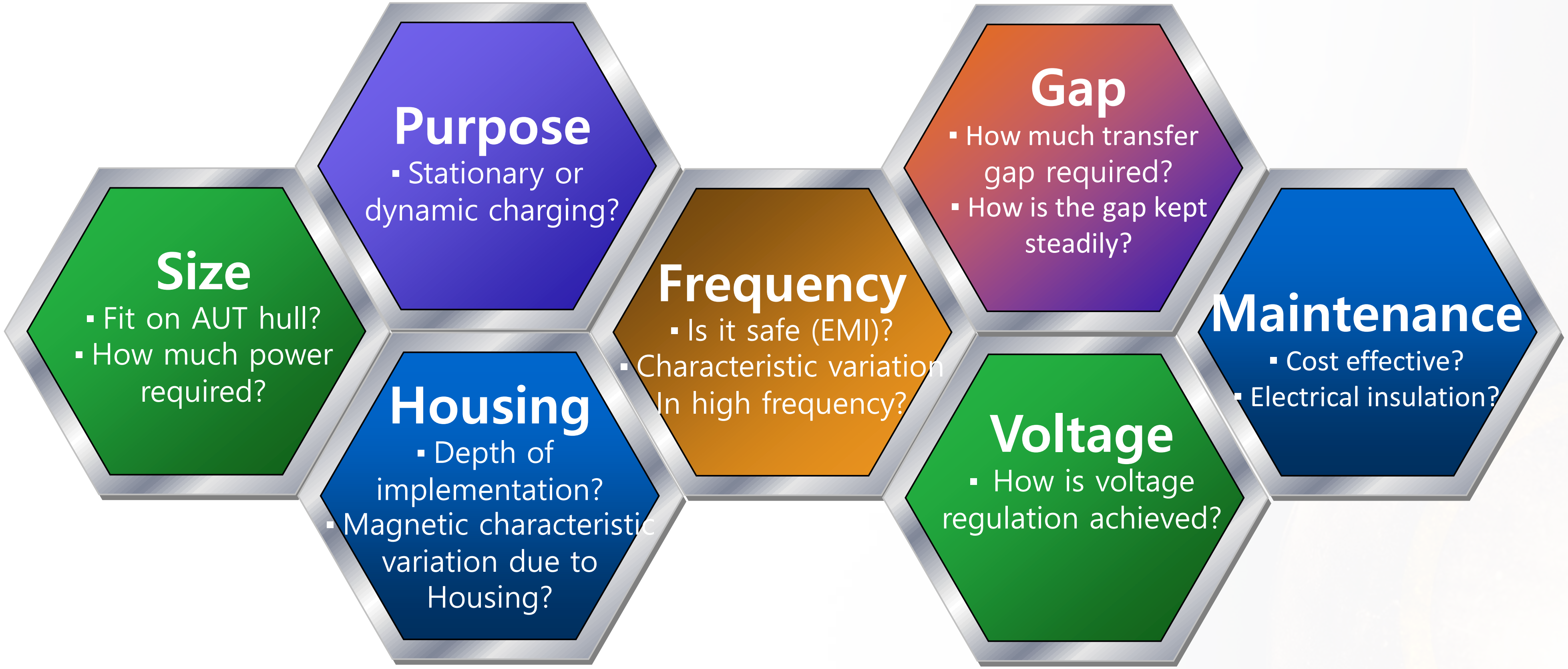
Efficiency of prototype





Distance	DC Input [Watt]		AC Pin [Watt]			AC Pout [Watt]			DC Output [Watt]		Transfer Efficiency			DC-DC Efficiency	
	Air	Seawater	FEKO	Air	Seawater	FEKO	Air	Seawater	Air	Seawater	FEKO	Air	Seawater	Air	Seawater
10mm	5.33	4.60	3.87	4.26	4.24	3.51	3.78	3.89	3.64	3.48	90.70%	88.65%	91.68%	68.20%	69.67%
20mm	6.77	6.77	5.70	5.65	5.89	5.10	5.08	5.05	4.61	4.63	89.47%	89.91%	85.74%	68.07%	68.35%
30mm	8.88	7.88	8.40	7.42	6.81	7.50	6.89	6.12	5.98	5.38	89.29%	92.88%	89.87%	67.29%	68.24%
40mm	14.10	13.32	13.0	11.55	11.42	11.2	9.35	9.18	8.22	7.97	86.15%	80.95%	80.40%	58.27%	59.86%
50mm	20.76	17.21	19.5	15.24	14.14	16.0	12.79	11.5	11.06	10.07	82.05%	83.95%	81.33%	53.28%	58.49%
60mm	23.43	25.65	28.0	17.62	18.47	22.0	12.36	12.89	10.77	11.90	78.57%	70.15%	69.81%	45.98%	46.40%

5. Consideration for AUT WPT system



For the extension of WPT technology in AUTs

- **The standards (rated power, voltage, frequency, gap and etc.) should be established.**
- **A joint research is necessary. (Marine + Electrical + Mechanical + …)**
- **It needs to clarify how/what the implemented WPT affects AUT practically.**

Question?

THANK YOU