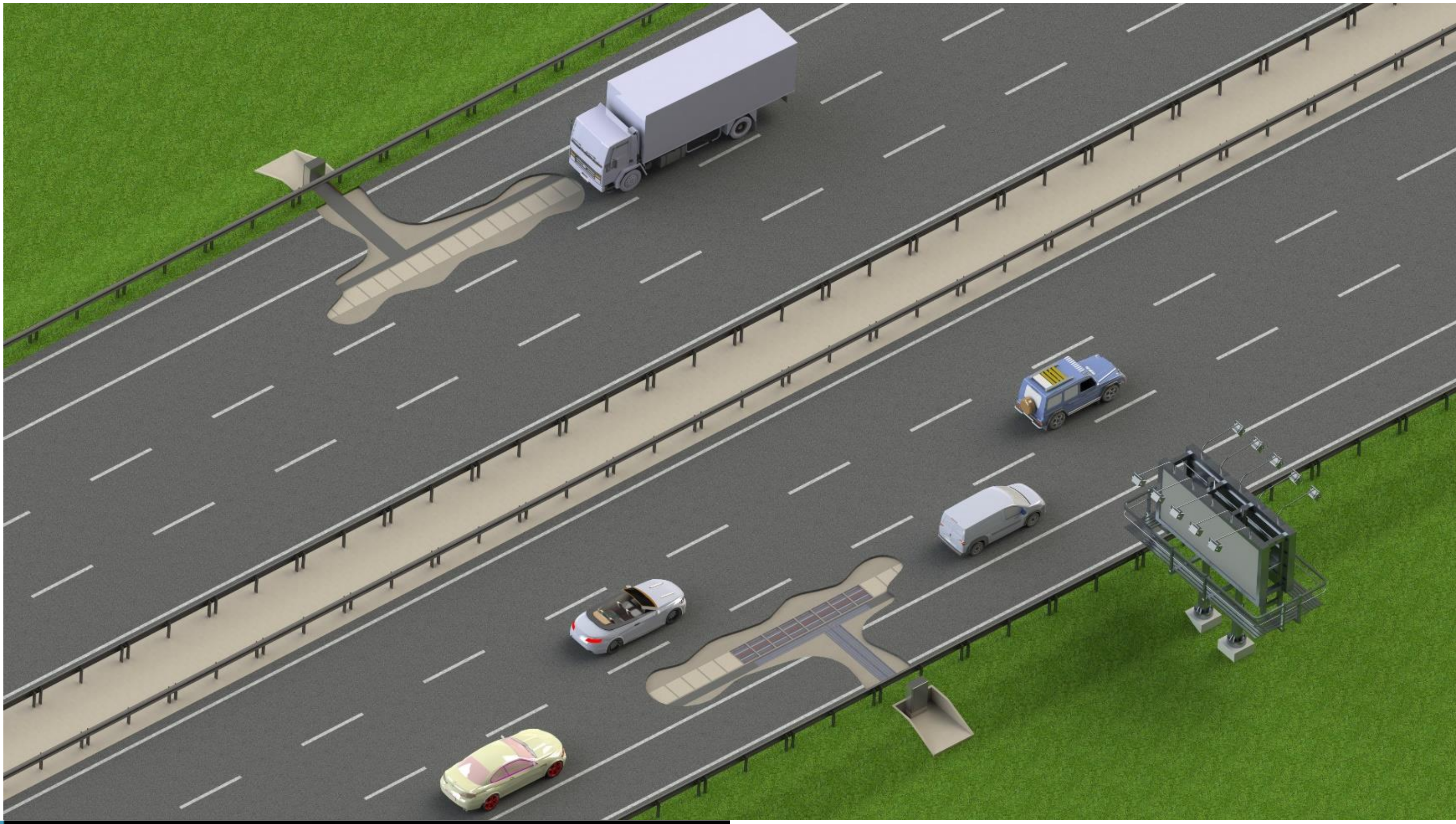

WHY YOU NEED MAGNETIC MATERIALS FOR WIRELESS POWER TRANSFER

MAGMENT

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WHITE PAPER

1. INTRODUCTION

The main purpose of this paper is to explain in a straightforward, simple and convincing manner the main practical benefits of using magnetic material in Wireless Power Transfer (WPT) systems. The analyzed problem is defined in Section 2. A simulation scenario is presented in Section 3, where two 50 kW WPT systems, one having a magnetic core and the other one not having a magnetic core, are compared in terms of overall electromagnetic performance. Finally, conclusions are presented in Section 4.

2. PROBLEM DEFINITION

A WPT system, in its basic form, consists of two coils placed at a certain distance from each other. The coils are magnetically coupled, so that when one coil is supplied with AC current, an AC voltage is induced in the other coil and vice versa. This magnetic coupling enables a wireless transfer of power from one coil (termed the transmitter or Tx coil) to the other coil (termed the receiver or Rx coil), by means of a time varying magnetic field. The receiver coil can be placed on a moving electric vehicle, while the transmitter coil can be placed in the road infrastructure, enabling thereby wireless charging of the electric vehicle battery. The coil located in the vehicle is therefore commonly called the Vehicle Assembly (VA), while the coil installed in the ground is commonly called the Ground Assembly (GA).

From the basic explanation of a WPT system it is evident that the essential components of the WPT system are the two coils. However, in WPT systems consisting of just two coils, without any magnetic material, relatively high coil currents are required to achieve feasible WPT system power levels. Consequently, high currents in the coils generate strong high-frequency electromagnetic fields in the space surrounding the coils. These fields represent a huge problem in wireless charging applications, because the exposure of people to high electromagnetic field emissions can cause health problems, especially users of electronic devices such as peacemakers.

For this reason, it is of great practical interest to lower the field emissions in the vicinity of WPT systems, without impacting the output power and the efficiency of the system. For these reasons, aluminum shields are added above the VA to reduce the field emissions experienced by the vehicle passengers. However, the same approach cannot be efficiently applied when it comes to reducing the field emissions on the vehicle sides, next to the road. The only way this can be achieved is to reduce the coil currents, but without reducing the system power.

The idea is to “guide” the magnetic field generated by the GA and localize it to the space where the VA is installed, thereby reducing the electromagnetic field emissions in the vicinity of the vehicle, without impacting the power transfer or the system efficiency. This can only be achieved by adding a magnetic core underneath the GA coil, thereby eliminating the magnetic field below the coil, and directing the electromagnetic field to the space where the VA is located.

3. ANALYSIS OF MAGNETIC CORE IMPACT ON WPT SYSTEM PERFORMANCE

In order to demonstrate the impact of the magnetic core on WPT system performance, two WPT systems for power 50 kW and frequency 85 kHz, with identical VA pads, but with different GA pads (one with and the other without a magnetic core) are compared with respect to overall electromagnetic performance. Both systems have identical overall GA coil dimensions, while GA coil current is adjusted for each variant in order to transfer full power 50 kW at a given coil-to-coil distance 350 mm and at given frequency 85 kHz, while assuming a lateral misalignment of 100 mm between GA and VA pads. The results of this comparison are shown in Table 1.

Table 1. Comparison of two 50 kW WPT systems with and without GA magnetic core

	Symbol	With Magment core	Without any core	%-Difference vs. without core
Coil-To-Coil Distance (mm)	D_{cc}	350	350	**0 %**
Lateral misalignment (mm)	Δy	100	100	**0 %**
Output power (kW)	P_{out}	50	50	**0 %**
Input power (kW)	P_{in}	53	53	**0 %**
Transfer efficiency (%)	η	94	94	**0 %**
Coupling factor	k	0.15	0.11	**+ 36 %**
GA coil current (A_{RMS})	I_{AC1}	103	198	**–48 %**
GA coil voltage (kV_{RMS})	U_{AC1}	2	2	**0 %**
GA coil temperature (°C)	θ_{w1}	85	142	**–40 %**
Magnetic field at distance 1.5 m from the transmitter pad (µT)	B	15	21	**–29 %**

The GA pad without core is shown in Fig. 1, while the GA pad with core is shown in Fig. 2.

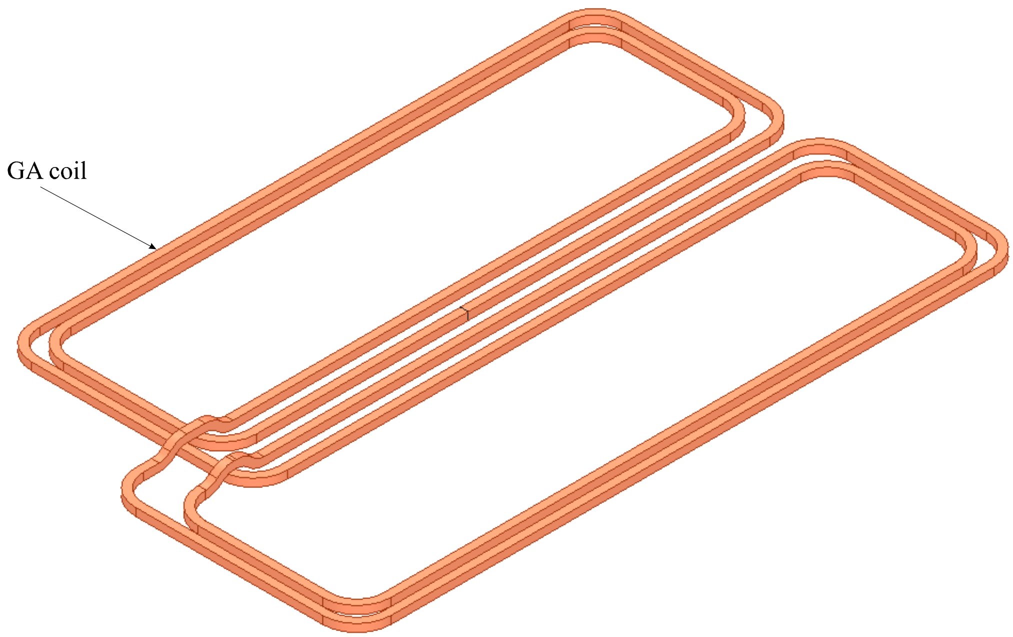

Fig. 1 GA pad without core (self-inductance is 19 µH)

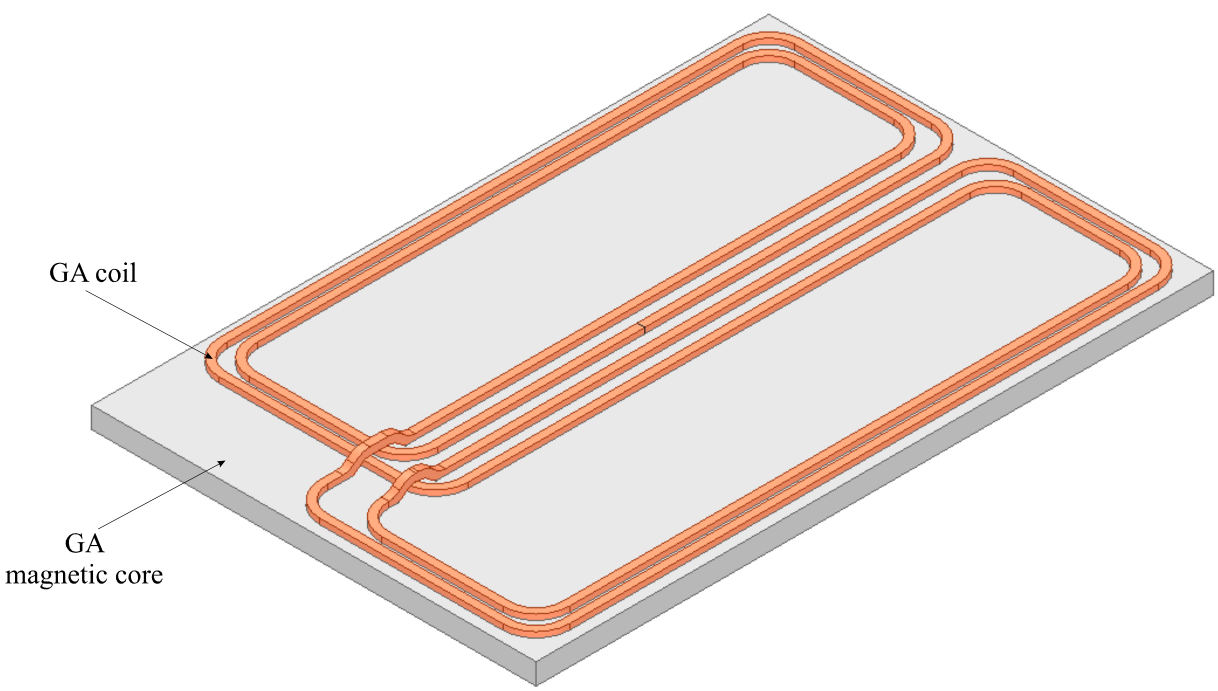

Fig. 2 GA pad with core (self-inductance is 35 µH)

From Table 1 it can be seen that by adding a magnetic core to the system, the magnetic field emissions are significantly decreased (by 29 %), while power transfer is maintained at the same level (50 kW) for a given coil-to-coil distance (350 mm) and a given lateral misalignment between the GA and VA pads (100 mm).

In addition, Table 1 shows that the current in the GA coil, required to transfer power 50 kW over a coil-to-coil distance of 350 mm, is significantly decreased (approximately by half) when the core is added. This can be explained by inspecting figures 3 and 4, where in the case with core (Fig. 4) the magnetic field underneath the coil is eliminated, while the magnetic field is directed above the GA coil. Because half of the field (underneath the GA coil) is eliminated, the same field above the GA coil can be obtained by only half of the current in the coil.

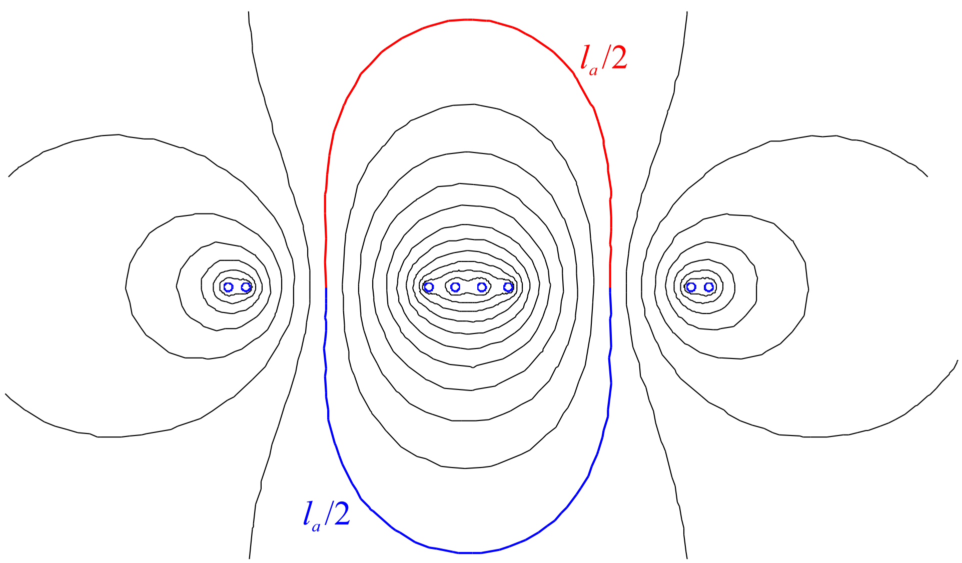

Fig. 3 GA magnetic field without core

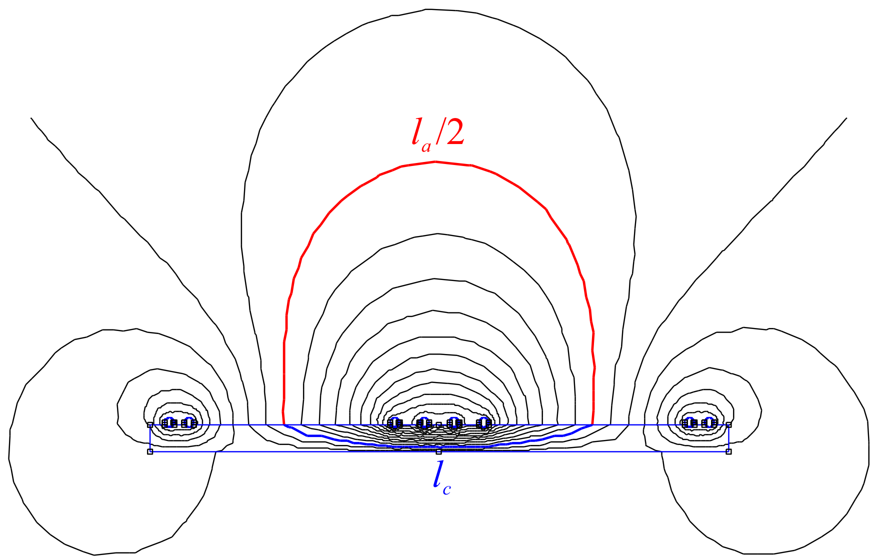

Fig. 4 GA magnetic field with core

The decreased current in the GA coil also leads to decreased winding losses (Joule losses) in the WPT system with the magnetic core with respect to the WPT system without a magnetic core. However, in the WPT system with a magnetic core there also exist magnetic losses (hysteresis and Eddy current losses), which don't exist in the system without a core. Still, from Table 1 it can be seen that the WPT system with core can achieve the same power efficiency as the WPT system without a core, despite having additional core losses which are not present in the system without core.

It needs to be pointed out that the efficiency given in Table 1 is the electromagnetic efficiency of the WPT system, which doesn't consider the losses in the power electronics inverter and the cables which are used to supply the GA pad with power. Because of the significantly lower current required by the WPT system with core with respect to the WPT system without core, the losses in the power electronics inverter and the cables will be significantly lower, which will result in higher overall efficiency of the WPT system including power electronic converter and cables.

The efficiency of the WPT system with core can even be increased above the efficiency of the WPT system without core, by simply making the core thicker. The core in this analysis is 50 mm thick, which is a minimum value, required from a mechanical point of view, if the pad is to be built into the road infrastructure. From an electromagnetic point of view, the core can always be made thicker, thereby decreasing the magnetic field in the core, and significantly decreasing the core losses, thereby improving efficiency. Of course, a thicker core would also have higher mass and higher cost. The presented solution represents the most cost-efficient solution which still achieves the same efficiency as the WPT system without a core.

From Table 1 it can also be seen that the voltage at GA coil terminals is the same (2 kV_{rms}) for both systems, with and without magnetic core, which means that the same insulation material can be used in both cases. For the WPT system without magnetic core, the inductance is approximately two times lower than for the system with magnetic core (19 µH for the case without core and 35 µH with core). This means that the coil impedance is approximately two times higher for the system with magnetic core. Because the current in the system with magnetic core is two times lower than for the system without magnetic core for the same power and coil-to-coil distance, while GA coil impedance is two times higher for the system with magnetic core than for the system without magnetic core, it can be concluded that the voltage across GA coil terminals will be the same in both cases. It can be concluded that by adding a magnetic core, although the coil impedance is significantly increased, there is no significant increase in coil voltage for the same power, because simultaneously the GA coil with magnetic core requires significantly lower current for the same power output and coil-to-coil distance.

Also, from Table 1 the temperature of the GA coil is much lower for the WPT system having a magnetic core. This is because both WPT systems have the same losses, while the magnetic core acts as an additional heat sink for the winding. The temperatures from Table 1 are the maximum temperatures that would be reached after infinitely long continuous operation with full power 50 kW. It is evident that the system without core couldn't continuously transfer power 50 kW, because the system would have to be turned off before reaching the temperature 142 °C listed in Table 1, to prevent insulation failure due to overheating.

Fig. 5 shows the magnetic field in the vicinity of the WPT system with magnetic core, while Fig. 6 shows the magnetic field plot without magnetic core. In all figures, X is the driving direction, while Y is perpendicular to the driving direction. In both cases the systems are operating at full power 50 kW and with 100 mm lateral misalignment and with 350 mm coil-to-coil distance. Both systems are designed for use on a heavy-duty vehicle, where it is assumed that the road width is 3 m. It is assumed that people are allowed to stand beside the edge of the road (Y = 1.5 m away from the center of the GA pad). For all distances higher than 1.5 m from the center of the GA pad, the system with core produces a magnetic field that is lower than 15 μT_{rms} (21.21 μT_{peak}), which is the maximum allowed field with respect to pacemakers[1].

[1] International Commission on Non-Ionizing Radiation Protection (ICNIRP) 2010; ICNIRP guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz TO 100 kHz).

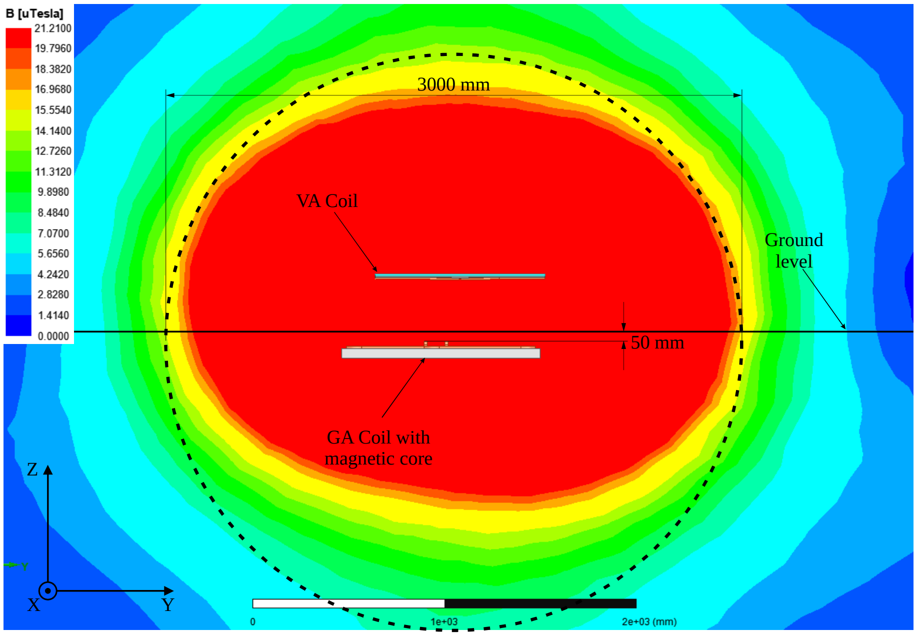

Fig. 5 Magnetic field in the vicinity of **GA pad with magnetic core**
and transferred power 50 kW at coil-to-coil distance 350 mm and lateral misalignment 100 mm
(limit value of 15 μT_{RMS} (21.21 μT_{Peak}) is achieved at **1500 mm** from Tx pad center)

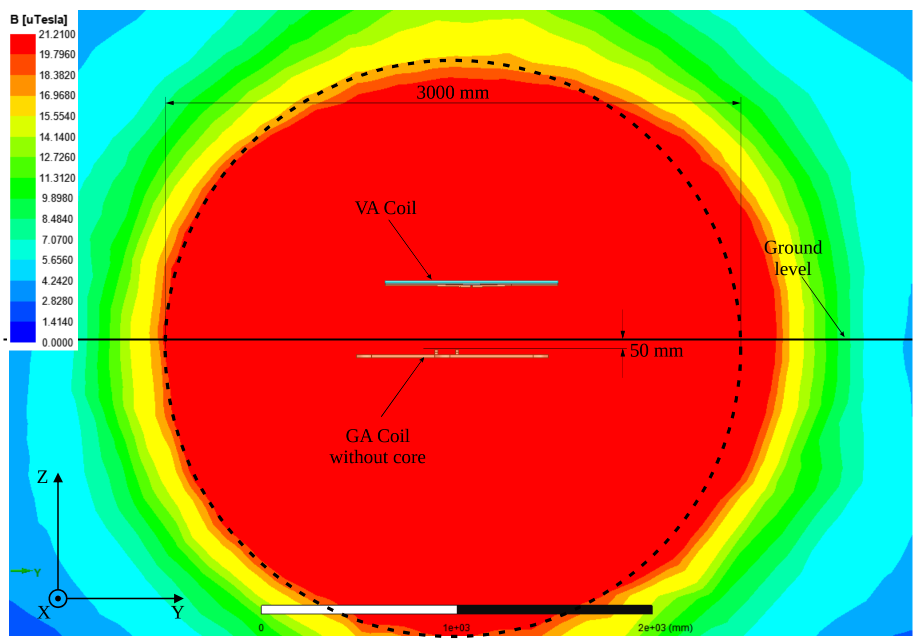

Fig. 6 Leakage field in the vicinity of **GA pad without core**
and transferred power 50 kW at coil-to-coil distance 350 mm and lateral misalignment 100 mm
(limit value of 15 μT_{RMS} (21.21 μT_{Peak}) is achieved at **1700 mm** from Tx pad center)

On the other hand, the system without magnetic core produces higher magnetic fields at distances where people might get exposed to the dangerous magnetic field levels. This is once again confirmed by inspecting Fig. 7, where the magnetic field distribution at distance Y = 1.5 m from center of both systems is shown.

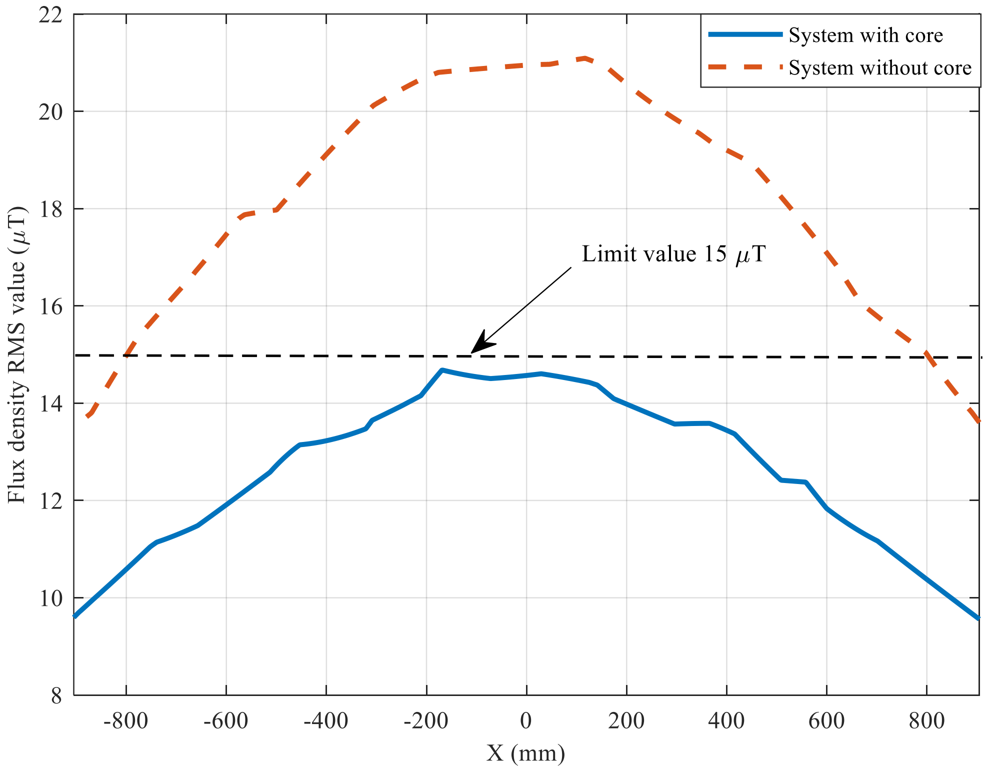

Fig. 7 Magnetic field distribution at a distance of Y = 1.5 m from the center of both systems.

4. CONCLUSIONS

The analysis conducted in this paper shows that the addition of a magnetic core underneath the GA coil of a WPT system can bring following benefits:

- Significantly (almost 50 %) lower current in the GA coil for the same power, coil-to-coil distance, and GA coil geometry.
- Significantly lower magnetic field emissions in the vicinity of the WPT system, for the same power, coil-to-coil distance, and GA coil geometry.
- Significantly lower GA coil temperature for the same power, coil-to-coil distance, and GA coil geometry.