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Qi Specification version 2.0

Part 10: MPP System Specification

National foreword

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(IEC 63563-10:2025)

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Spezifikation
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QI SPECIFICATION VERSION 2.0 –

Part 10: MPP System Specification

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Qi Specification

MPP System Specification

Version 2.0

April 2023

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Table of Contents

Table of Contents	2
List of Figures	6
List of Tables	9
1 General Description	10
1.1 Introduction	10
1.1.1 Scope	10
1.1.2 Document organization	10
1.1.3 Design goals	10
1.1.4 BPP and MPP interoperability	12
1.1.5 Related documents	12
1.2 Architectural overview	13
1.2.1 System Description	13
1.2.2 System block diagrams	14
1.3 Glossary	16
1.3.1 Definitions	16
1.3.2 Acronyms	17
1.3.3 Symbols	17
1.4 System Model vs Spec.	18
2 Authentication Protocol	19
2.1 Authentication	19
3 Coil Design	20
3.1 Introduction and Background	20
3.2 PTx Coil System Model	20
3.2.1 Mechanical Construction	20
3.2.2 Electrical Properties	31
3.3 PRx Coil System Model	33
3.3.1 Mechanical Construction	33
3.3.2 Electrical Properties	42

3.4	Properties of Mated Coil System Models	43
3.4.1	Electrical measurement under mated conditions	43
3.5	Coil Specifications.....	44
3.5.1	PRx Coil Specifications	44
3.5.2	PTx Coil Specifications.....	50
4	Power Delivery.....	57
4.1	Power Profiles (BPP + MPP)	57
4.1.1	Specifications.....	57
4.1.2	Recommendations.....	57
4.1.3	Specification Notes	57
4.2	Power Receiver Functional Block Diagram	58
4.2.1	System Model	58
4.3	Power Transmitter Functional Block Diagram	65
4.3.1	System Model	65
4.4	Operating Frequency	68
4.4.1	System Model	68
4.4.2	Specifications.....	68
4.5	Object Detection	68
4.5.1	System Model	68
4.5.2	Specifications.....	69
4.6	Digital Pings 128kHz/360kHz	69
4.6.1	Need For Digital Pings 128kHz / 360kHz.....	69
4.6.2	Specifications.....	76
4.7	K Estimation	78
4.7.1	System Model	78
4.7.2	Specifications.....	82
4.8	Output Impedance and Load Transients	83
4.8.1	System Model	83
4.9	Set Pr_max	86
4.9.1	Background.....	86
4.9.2	System Model	86
4.9.3	PTx Specifications	92
4.9.4	PTx Specification Notes.....	92
4.10	Power Transfer Control.....	92
4.10.1	Intro and Background (Informative)	92

4.10.2	System Model	92
4.10.3	End-to-End Control Specifications	98
4.11	Mitigation of Side Effects of Cd at MPP Frequency	101
4.11.1	System Model	101
4.11.2	Specifications.....	104
4.12	Cloak.....	104
4.13	Common-mode Noise	104
5	Communications Physical Layer	105
5.1	Introduction	105
5.2	Frequency Shift Keying (PTx to PRx)	105
5.2.1	System Model	106
5.2.2	Frequency Shift Keying Specifications	108
5.3	Amplitude Shift Keying (PRx to PTx)	109
5.3.1	Modulation Scheme	109
5.3.2	System Model	110
5.3.3	ASK Specifications	115
6	Foreign Object Detection	117
6.1	Background	117
6.2	Open-air Q-Test (pre-power transfer FOD method).....	117
6.2.1	Introduction.....	117
6.2.2	Movement Timer.....	120
6.2.3	Settling Timer	120
6.2.4	Glossary	120
6.2.5	Open-air Q-Test Specifications.....	120
6.2.6	Theory of Operation.....	121
6.2.7	PRx movement and digital ping	125
6.3	MPP Power Loss Accounting (in-power transfer FOD method)	126
6.3.1	Introduction.....	126
6.3.2	MPLA Specifications	127
6.3.3	MPLA Equations.....	130
6.3.4	Eco-System Scaling	131
6.3.5	Process of Extracting LQK-Dependent Coefficients.....	133
6.3.6	FO power estimation error outside 2x2 cylinder	134
6.3.7	FO Detection Thresholds	135
6.3.8	In-Power FOD Action	138

6.3.9	Accessory Power Loss Requirements	140
6.3.10	Error Budget	140
6.3.11	Measuring coil current	147
7	Annex	149
7.1	PTx Working with Legacy PRx.....	149
7.1.1	Background.....	149
7.2	Mitigation of Saturation for BPP	149
7.2.1	System Model	149
7.2.2	SHO Specifications	153
7.3	Loss-Split Modeling: A framework for calculating localized eddy-current losses	153
7.3.1	Introduction.....	153
7.3.2	Comparison between the standard T-Model and Loss-Split Model	155
7.3.3	Determining the Loss-Split Model Parameters	156
7.3.4	Calculating Power Loss using Loss-Split Model	157
7.3.5	Loss-Split Model Validation	158
7.4	Resistive Coupling Factor	158
7.4.1	Introduction.....	158
7.4.2	Definition of Mutual Resistance and Kr.....	158
7.4.3	Cause of Mutual Resistance	159
7.4.4	Why is Kr non-negligible.....	161

List of Figures

Figure 2.1.3 : 1 Multipole magnet design that tightly couples strong permanent magnetic fields within the region of the magnet array	11
Figure 2.1.3 : 2 Accurate magnetic alignment within a 2mm radius (without case and with silicone case)	11
Figure 2.2.2 : 3 System block diagram	15
Figure 2.2.2 : 4 MPP PTx functional diagram	15
Figure 2.2.2 : 5 MPP accessory functional diagram (e.g., PRx case, wallet, automotive dash-mount)	15
Figure 2.2.2 : 6 MPP PRx functional diagram	16
Figure 4.2.1.1 : 7 Exploded view of PTx coil system model	20
Figure 4.2.1.3 : 8 Exploded view of the Coil Module for the PTx Coil System Model	21
Figure 4.2.1.3 : 9 Side view of PTx Coil Module	22
Figure 4.2.1.3 : 10 Top view of PTx ferrite	22
Figure 4.2.1.4 : 11 Magnet Array top view	24
Figure 4.2.1.5 : 12 Magnet assembly (Cross-section)	26
Figure 4.2.1.6 : 13 Side view of Bottom Enclosure	27
Figure 4.2.1.8 : 14 Side view of PTx coil system model assembly	29
Figure 4.2.1.9.1 : 15 Transmitter orientation magnets (Top View)	30
Figure 4.2.1.9.1 : 16 Transmitter Orientation Magnet Dimensions and Polarity	31
Figure 4.3.1.1 : 17 Exploded view of PRx coil system model	34
Figure 4.3.1.4 : 18 Exploded view of the coil module for the PRx coil system model	35
Figure 4.3.1.4 : 19 Cross-section of the coil module for the PRx coil system model	36
Figure 4.3.1.4 : 20 Cross-sectional view of coil for the PRx coil system model	36
Figure 4.3.1.4 : 21 Top view of PRx coil system model	37
Figure 4.3.1.5 : 22 Magnet of the PRx coil system model (top view)	40
Figure 4.3.1.5 : 23 Magnet of the PRx coil system model (side view)	40
Figure 4.3.1.5 : 24 Magnetic field of the PRx coil system model	41
Figure 4.3.1.5 : 25 Orientation magnet of the PRx coil system model (side view)	41
Figure 4.3.1.7 : 26 Cross-sectional view showing assembly of PRx coil system model	41
Figure 5.1.3.1 : 27 MPP minimum power delivery requirement shall be $P_I \geq 15W$ for $0mm \leq z \leq 2mm$, $0mm \leq r \leq 2mm$	57
Figure 5.1.3.1 : 28 An MPP PTx shall be able to deliver $P_I \geq 5W$ to an BPP system model PRx for $0mm \leq z \leq 3mm$, $0mm \leq r \leq 8mm$	58
Figure 5.1.3.1 : 29 Cross section view of the system model indicating the "z" gap	58
Figure 5.2.1.1 : 30 System model PRx circuit topology (with BPP and MPP compatibility)	59
Figure 5.2.1.3.1 : 31 Cantilever Equivalent Circuit	60
Figure 5.2.1.3.2.1 : 32 Efficiency vs Crx: sweep of Crx at the maximum coupling position in the system model shows that efficiency is low when $C_{rx} < 300nF$ (system is capacitive)	62
Figure 5.2.1.3.2.1 : 33 Bode plot of $Z_{in}(s)$ at maximum coupling location with two different Crx values. With $C_{rx}=60nF$, the system impedance is capacitive, which is undesirable.	63

Figure 5.2.1.3.2.1 : 34 Bode plot of $G(s)$ at maximum coupling location with two different C_{rx} values. $C_{rx}=710\text{nF}$ has ~1.4dB higher gain than $C_{rx}=60\text{nF}$.	63
Figure 5.2.1.5 : 35 System model P_{rx} V_{rect}/I_{rect} profile	65
Figure 5.3.1 : 36 PTx power stage block diagram	66
Figure 5.3.1.1 : 37 Definition of inverter phase θ	66
Figure 5.6.1 : 38 MPP Power Negotiation Flow	70
Figure 5.6.1 : 39 Top-level diagram	72
Figure 5.6.1 : 40 Digital Ping Flowchart	73
Figure 5.6.1 : 41 Identification 128kHz Flowchart	74
Figure 5.6.1 : 42 Identification 360kHz Flowchart	75
Figure 5.6.1 : 43 Configuration Flowchart	76
Figure 5.7.1.2.1 : 44 E0 and E1 Fit Example	80
Figure 5.7.1.2.1 : 45 Kest E0 and E1 Extraction Flow	80
Figure 5.7.1.4 : 46 Example PTx/PRx Kest Error Stack-up	82
Figure 5.8.1.1 : 47 Typical Output Impedance Plot (V_{rect} vs I_{rect})	84
Figure 5.8.1.2.1 : 48 V_{rect} timing diagram during load step procedure in the system model	85
Figure 5.8.1.2.2 : 49 V_{rect} timing diagram during load dump procedure in the system model	85
Figure 5.9.2.3.1 : 50 Set Pr_{max} Overall Flow	88
Figure 5.9.2.3.1 : 51 Example Time Sequence	89
Figure 5.9.2.3.2 : 52 Gain Measurement Flow	90
Figure 5.9.2.3.3 : 53 Set initial V_{rect_target} and Pr_{max} based on $G1 \cdot G2$	91
Figure 5.9.2.3.3 : 54 Pr_{max} vs $G1 \cdot G2$	91
Figure 5.10.2.2.1 : 55 Tx Voltage Control Flow Chart	95
Figure 5.10.2.3.3 : 56 Ilim control diagram	97
Figure 5.11.1.0.1 : 57 V_{rect} vs inverter phase at light load	101
Figure 5.11.1.0.1 : 58 Output impedance with 50 and 120 degrees inverter phase	102
Figure 5.11.1.0.2 : 59 Gain (V_{rect}/V_{in}) with and without C_d	102
Figure 5.11.1.0.2 : 60 Load release from 7W to 0W, with and without C_d , and with mitigations implemented in the system model	103
Figure 5.11.1.0.3 : 61 ZVS state with and without C_d , and with mitigations implemented in the system model	103
Figure 6.1 : 62 MPP Comms Physical System Model	105
Figure 6.2.1.1 : 63 System Model for FSK Transmitter	106
Figure 6.2.1.2 : 64 System Model for FSK Receiver	107
Figure 6.2.1.2 : 65 Sample Waveform: Digital Ping 360 kHz AC2 node voltage	108
Figure 6.3.1 : 66 (a) Primary Resonant Capacitor Amplitude and (b) Primary Resonant Capacitor Phase Shift	110
Figure 6.3.2.1 : 67 System Model for ASK Modulator at 128 kHz	111
Figure 6.3.2.1 : 68 System Model for ASK Modulator at 360 kHz	112
Figure 6.3.2.1 : 69 Representative Waveforms for ASK Modulator at 360 kHz	112
Figure 6.3.2.2 : 70 System Model for ASK Receiver	113
Figure 6.3.2.3 : 71 ASK Modulation Trends for (a) DC Load Current and (b) Capacitor Modulation	114

Figure 7.2.1 : 72 Detection Capability V.S. Thermal Requirements .	118
Figure 7.2.1 : 73 Simplified flow diagram for open-air Q test	119
Figure 7.2.6.1 : 74 Implementation of how to measure ring response	121
Figure 7.2.6.1.0.1 : 75 bias ping configuration	122
Figure 7.2.6.4.2 : 76 PRx replaced before the movement timer expires to prevent false fo flag	124
Figure 7.2.7 : 77 Example of q-deflection profile when Prx is approaching ptx	126
Figure 7.3.4.2 : 78 Eco-System Scaling Diagram	133
Figure 7.3.5 : 79 Linear fit error for coil and friendly metal losses. The resistances Rtx and Rrx represent the free-air coil resistances at the switching frequency.	134
Figure 7.3.6 : 80 MPLA estimation error for P_FO grows monotonically away from origin.	135
Figure 7.3.7.2 : 81 15W PFO error distribution with and without FO at 85° critical heating radius (scenario 2: Q-test does detect no FO)	137
Figure 7.3.7.2 : 82 10W PFO error distribution with and without FO at 70° critical heating radius (scenario 1: Q-test detects FO)	137
Figure 7.3.8.1 : 83 Recommended flowchart for PTx FOD action.	139
Figure 7.3.10.3 : 84 PRx Compliance Test pFO Distribution	145
Figure 7.3.10.5 : 85 Compliance Test Ppr shift explanation for Scenario 2 (15W)	147
Figure 8.2.1.1 : 86 Comparison of PTx current with and without SHO	150
Figure 8.2.1.2 : 87 System Model SHO detection flowchart	151
Figure 8.2.1.3 : 88 System Model SHO mitigation flowchart	152
Figure 8.3.1 : 89 Simulation based power accounting flow	154
Figure 8.3.1 : 90 Loss-Split Power Accounting Flow	154
Figure 8.3.2 : 91 Standard T-Model	155
Figure 8.3.2 : 92 Loss-Split T-Model	155
Figure 8.4.2 : 93 Mutual Resistance Model at a Single Frequency	159
Figure 8.4.3.2 : 94 Non-linear B-H curve introduces phase offset between PTx current and the integral of PRx induced voltage, where the out-of-phase component is captured by mutual resistance	161
Figure 8.4.4 : 95 Example values of Kr measured with a mated MPP PTx/PRx coil sample	162

List of Tables

Table 4.2.1.3 : 1 Mechanical dimensions for the coil module of the PTx coil system model	23
Table 4.2.1.5 : 2 Magnetic field specifications for magnet array	26
Table 4.2.1.7 : 3 Mechanical dimensions for the bottom enclosure of the PTx coil system model	28
Table 4.2.1.8 : 4 Assembly dimensions of PTx coil system model	29
Table 4.2.1.9.1 : 5 Flux density at 0.85mm from PTx orientation magnet surface	31
Table 4.2.2.1 : 6 Electrical Parameters of the PTx Coil System Model in Free-Air	32
Table 4.3.1.4 : 7 Assembly specifications of coil module for the PRx coil system model	36
Table 4.3.1.4 : 8 Mechanical specifications of the PRx coil system model	38
Table 4.3.1.5 : 9 Magnet properties of the PRx coil system model	39
Table 4.3.1.7 : 10 Assembly specifications for the PRx coil system model	42
Table 4.3.1.7 : 11 Mechanical dimensions of support plate	42
Table 4.3.2.1 : 12 Electrical Parameters of the PRx Coil System Model in Free-Air	42
Table 4.4.1 : 13 Mated electrical parameters (Test case: $r=0$, $z=0$ mm)	43
Table 4.4.1 : 14 Mated electrical parameters (Test case: $r=2$, $z=2$ mm)	43
Table 5.2.1.1 : 15 PRx series tuning configuration	59
Table 5.2.1.4 : 16 PRx electrical properties (system model)	64
Table 5.3.1.2 : 17 PTx power stage capacitor switches configuration	67
Table 5.3.1.3 : 18 PTx electrical properties (system model), during power transfer	67
Table 6.3.2.1 : 19 Selection of MOD_BASE	111
Table 7.2.4 : 20 Glossary	120
Table 7.3.2.3 : 21 Eco-System Parameter Representation	130
Table 7.3.4.1 : 22 Eco-System scaling terms exchanged between PTx and PRx at startup	131
Table 7.3.7.1 : 23 MPLA Scenarios	136
Table 7.3.10.2 : 24 Measurement Error Calculation for Scenario 1 (10W) and Scenario 2 (15W)	143
Table 7.3.10.3 : 25 pFO Error Budget Calculation	144

1 General Description

1.1 Introduction

1.1.1 Scope

This specification defines MPP (Magnetic Power Profile), an extension to Qi v1.3 BPP (Baseline Power Profile). Manufacturers can use this specification to implement PTx and/or PRx that are interoperable.

1.1.2 Document organization

The MPP (Magnetic Power Profile) Specification is organized as these documents:

1. MPP System Specification (this document)
2. MPP Communications Protocol Specification

MPP is an extension of the Baseline Power Profile (BPP) and utilizes some (but not all) features defined in the Extended Power Profile (EPP). Where relevant, refer to the Qi v2.0 Specification.

1.1.3 Design goals

Magnetic Power Profile (MPP) is an interface which allows for:

- Never missing the sweet spot - ease of attach through ring of magnets
- Ecosystem of powered and unpowered accessories
- Conveniently using your device while charging
- Delivering high power (15W) safely
- Preventing interference with vehicle key fobs without regulatory issues by operating at 360 kHz
- Compatibility with Qi 2.0 BPP products and maintaining near-parity backward compatibility with Qi 1.x BPP products

Sweet spot

The goal for MPP is to enable a new wireless charging experience for users where they will never miss the charging "sweet spot" and can consistently, efficiently, and safely charge their devices at high power. To achieve accurate alignment between the PTx and PRx coils, a circular array of magnets has been added that surround the coils. The magnetic alignment provides tactile feedback to the user guiding accurate placement even in the case where the user isn't directly looking at the PTx. Conveniently, the magnetic attachment enables users to use their device while it is charging and greatly simplifies docking functionality.

Magnet array

The magnet array has been carefully designed so that it can coexist with the wireless power transfer system to deliver high power transfer at high efficiency. Figure 2.1.3: 1 shows the multipole magnet design that tightly couples strong permanent magnetic fields within the region of the magnet array, keeping most of the strong fields away from the magnetic shielding material of the power transfer coils.

Because of the consistent accurate alignment, the magnetic state-space that the system must be designed to work across is reduced. Figure 2.1.3: 2 shows data from a study where 99.9% of placements aligned the PTx and PRx within a 2mm radius

¹. By reducing the state-space, the design of features like foreign object detection is simplified.

¹ The placement study used a case with integrated magnets as shown in Figure 2.1.3: 1

Benefits

The benefits of MPP also extend further than just wireless charging: it enables an ecosystem of powered and unpowered accessories. Because of the convenience of magnetic attach, it is expected that a new category of portable charging products will arise, and with this in mind, MPP has been designed to ensure that charging at 360 kHz will not cause interference with vehicle key fobs. All these benefits and experiences have been enabled in MPP while also being compatible with Qi 2.0 BPP and having nearly 100% backwards compatibility with Qi 1.x BPP.

Figure 2.1.3: 1 Multipole magnet design that tightly couples strong permanent magnetic fields within the region of the magnet array .

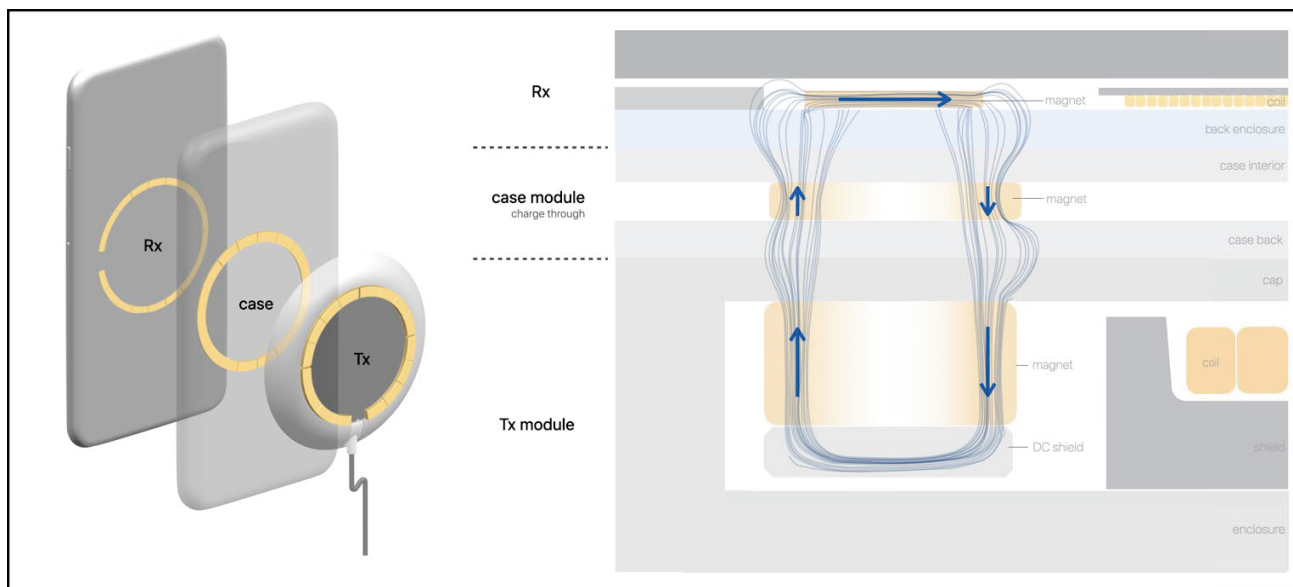
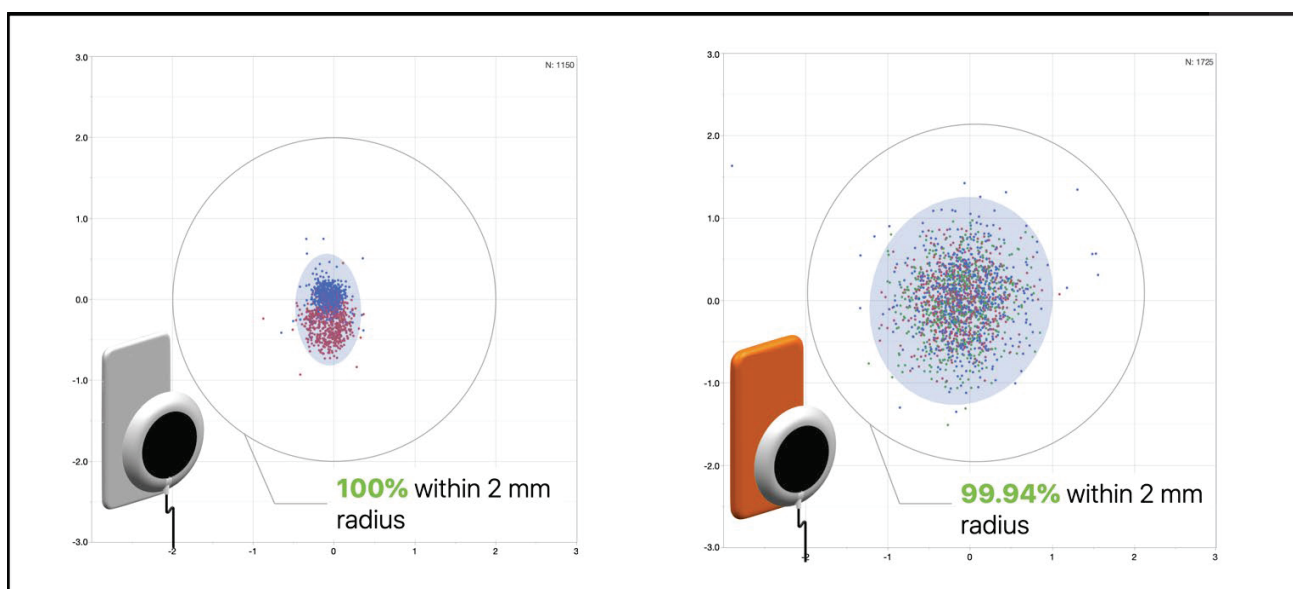


Figure 2.1.3: 2 Accurate magnetic alignment within a 2mm radius (without case and with silicone case).



1.1.4 BPP and MPP interoperability

Backward compatibility with PRx or PTx that do not support MPP is achieved by operating in BPP at up to 5 W:

- MPP PTx support operation as a BPP PTx (i.e., 5 W)
- MPP PRx support operation as a BPP PRx (i.e., up to 5 W)

To support both MPP and BPP, the system uses dynamic re-tuning. Dynamic re-tuning is achieved by switching appropriate capacitors in series with the Primary Coil in the PTx, and the Secondary Coil in the PRx.

Compared to BPP, this requires:

- For PTx: two additional capacitor values and two switches (e.g., MOSFETs)
- For PRx: one additional capacitor value and one switch

The magnet array resolves the problem of magnetic flux density in Shielding materials reaching saturation (associated with the deprecated magnetic alignment feature in Reference Designs A1, A5, A9). See § 4.2 PTx Coil System Model and § 4.3 PRx Coil System Model .

The deprecated magnetic alignment feature is described in Qi v1.2.2 Pt 4, Sec 2 Overview:

“NOTE Power Receivers that use thin magnetic Shielding have been found to experience reduced performance on Power Transmitters that contain a permanent magnet in or near the Active Area. Such Power Receivers may exhibit, for example, less positioning freedom and/or a longer charging time. For this reason Power Transmitter designs A1, A5, and A9 have been deprecated as of version 1.2 of the Qi Power Class 0 Specification.”

For BPP PRx that implements Shielding with a low saturation property, the magnet array in an MPP PTx can cause saturation. Such combinations of MPP PTx and BPP PRx can exhibit sub-harmonic oscillation. A solution for this is described in § 8.2 Mitigation of Saturation for BPP .

1.1.5 Related documents

General Documents

- Introduction
- Glossary, Acronyms, and Symbols

System Description Documents

- Mechanical, Thermal, and User Interface
- Power Delivery
- Communications Physical Layer
- Communications Protocol
- MPP Communications Protocol
- Foreign Object Detection
- NFC Tag Protection
- Authentication Protocol

1.2 Architectural overview

1.2.1 System Description

Figure 2.2.2: 3 and Figure 2.2.2: 4 show the MPP system architecture. Some elements are identical to those found in BPP. The system consists of the following blocks:

- External power source - in many cases a separate adapter such as a USB PD brick.
- Variable Voltage Supply - for voltage control of the power signal
- Inverter - a full-bridge DC/AC converter to produce the AC power signal
- Resonant circuit - switched capacitors in series with the coil to boost power transfer capability and to support MPP and BPP modes
- FSK (de-)modulator - enables communication from PTx to PRx using FSK
- ASK (de-)modulator - enables communication from PRx to PTx using ASK
- Rectifier - AC/DC conversion
- Controllable input current power converter - DC/DC converter that controls both its input current (drawn from the rectifier) and output voltage
- External power load - typically a battery and its associated host system e.g., application processor and peripherals

When the MPP system starts up, it will initially operate in Qi BPP frequency band to negotiate and determine whether the PTx and PRx both support MPP.

Power signal frequency

If MPP is supported, the system will restart and operate at a fixed power transfer frequency of 360kHz, which was selected to mitigate interference with nearby vehicle key fobs. This operating frequency is outside of the existing BPP frequency range and therefore requires different tuning capacitors on both the PTx and PRx for high and efficient power transfer. Because of this, both the PTx and PRx features switchable tuning capacitor banks to support both MPP and BPP.

Control of power transfer

To control the magnitude of power transfer, the DC voltage of the inverter is regulated and controlled. Additionally, modulation of the phase shift between the inverter's two half bridges may also be used at light loads. The details relating to power transfer is further discussed in the Power Delivery section.

Communication

To facilitate bidirectional communication, both FSK and ASK are used. On the PTx side, communications to the PRx uses FSK modulation of the power transfer frequency. The PRx side modulates its load to affect ASK communication to the PTx. MPP uses the same authentication scheme as EPP, but to speed up the authentication process, MPP uses fast FSK with 128 cycles per bit of data transferred. § 6 Communications Physical Layer specifies the changes to the physical layer.

Communication protocol

There are many additional features that have been implemented as part of MPP to enhance the user experience such as: free-air ping as pre-power FOD, enhanced power accounting as during-power FOD, thermal cloaking, data streams and new control loops. To enable these features, many changes have been implemented to the communications protocol which take effect after the system has switched into MPP mode. This protocol is in the document "MPP Communications Protocol."

Foreign Object heating

When an electrically conductive or ferromagnetic (with a high coercivity) Foreign Object (FO) is placed into the active area of the wireless power transfer (WPT) system, the AC magnetic field can cause the FO to heat up. If the FO reaches elevated temperatures this can compromise the system or its users. Foreign Object Detection (FOD) methods are implemented to prevent this from happening. MPP supports two FOD methods: open-air ping and MPP power loss accounting (MPLA).

Open-air ping

The open-air ping method takes place before power transfer, and it aims to detect FOs that are on the PTx surface before the PRx is placed. The advantage of this method is that there is no influence or impact by the PRx device, which is outside of the control of the PTx designer. Because this method is only dependent on the PTx, FOD performance can be guaranteed by design for this use case. This method is described in Annex B in the Foreign Object Detection book.

MPP power loss accounting (MPLA)

The second FOD method is applied during power transfer and can detect FOs regardless of when it is introduced into the WPT system. This method uses an enhanced power loss accounting model to estimate the magnitude of power loss that is causing FO heating and can throttle the power transfer magnitude to ensure the power lost in the FO won't cause excessive heating. One key feature of the improved model is the ability for PTx to adapt its model to consider the impact of the PRx on the PTx's losses and vice versa. This is important because the coil design and friendly metal on the PRx can also cause a change to the coil and friendly metal losses on the PTx. By taking this into account the FOD performance can be improved for more PTx and PRx combinations in the ecosystem. This method is described in § 7.3 MPP Power Loss Accounting (in-power transfer FOD method) .

Cloaking

There are several circumstances under which a PRx may want to request that wireless charging be paused or stopped. One common case is when the PRx's battery temperature is too high. Another scenario is at the end of the battery charge cycle where trickle charging is inefficient and it may be more desirable to wait until the PRx is further discharged before continuing charging. The cloaking feature is described in § 5.12 Cloak and in the document MPP Communications Protocol.

Power control

In addition to the (voltage) XCE control loop that is used to control power transfer, the PRx also regulates the current charging its battery. Typically, the battery charger current control loop is slow, but there are cases where the load power can suddenly drop (i.e. "load dump"). This can cause over-voltage on the PRx. To manage this, the battery charger current control loop coordinates with the XCE control loop to avoid over-voltage and other control instabilities. The two control loops are covered in § 5.10 Power Transfer Control .

Coil design

The coil system models and requirements are covered in § 4 Coil Design . This section includes details on the coil winding, shielding, magnet array, orientation magnets and externally observable compliance requirements in terms of magnetic alignment performance and the electrical parameters to enable BPP and MPP compatibility.

The coil system models provide nominal implementation models of an MPP PTx and MPP PRx. These are the basis for deriving externally observable requirements for compliant implementations of MPP PTx and PRx. While the system models provide a starting point for PTx or PRx designs, a compliant implementation may differ internally, if they comply with the externally observable requirements in the specification.

1.2.2 System block diagrams

Figure 2.2.2: 3 shows the system-level diagrams for a typical MPP system. There are also functional diagrams for three sub-blocks:

- MPP PTx: Figure 2.2.2: 4
- MPP accessory: Figure 2.2.2: 5
- MPP PRx: Figure 2.2.2: 6

Figure 2.2.2: 3 System block diagram.

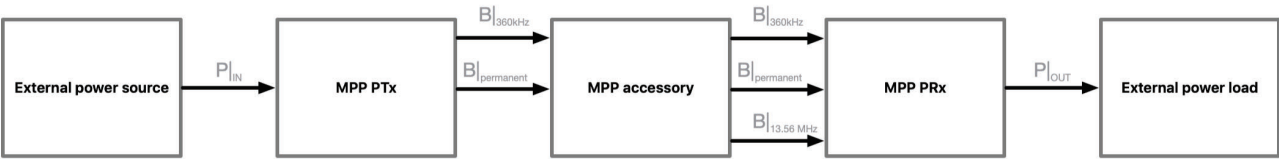


Figure 2.2.2: 4 MPP PTx functional diagram.

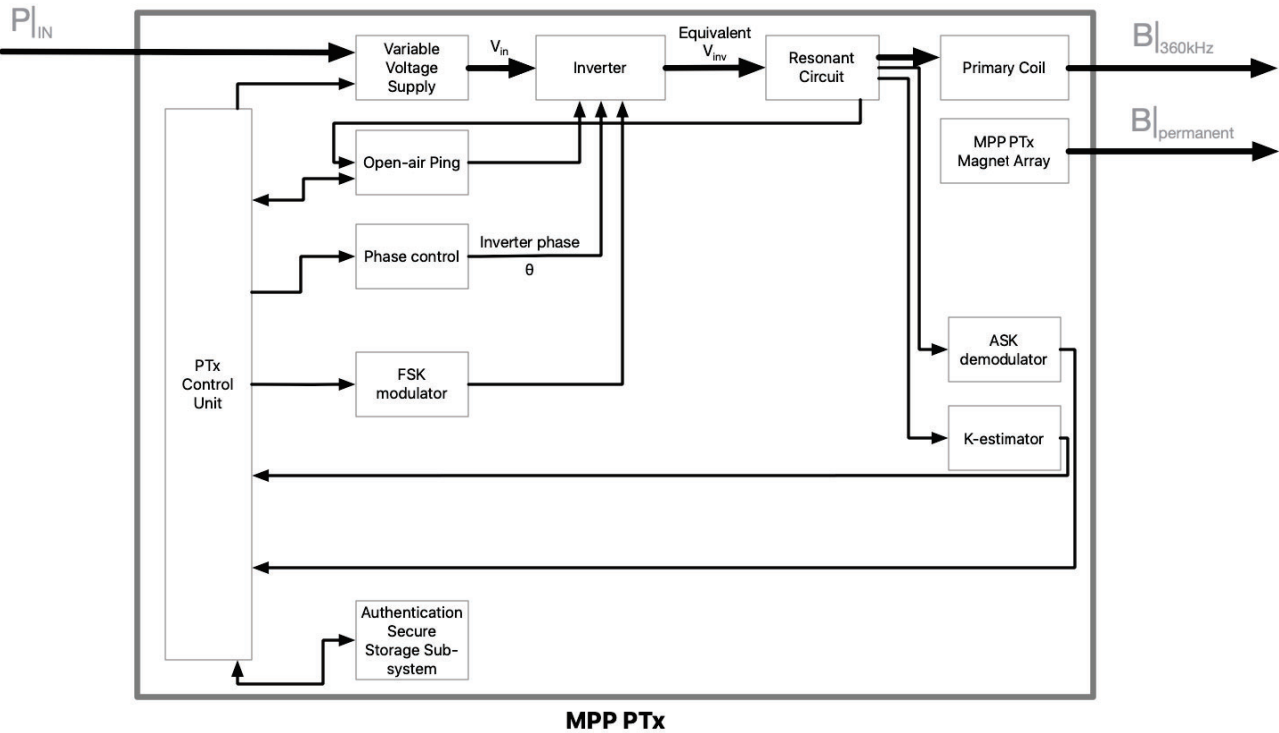
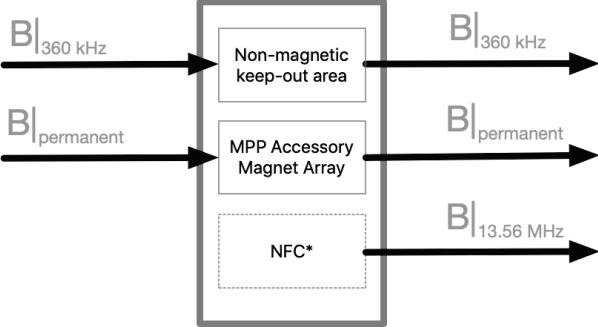
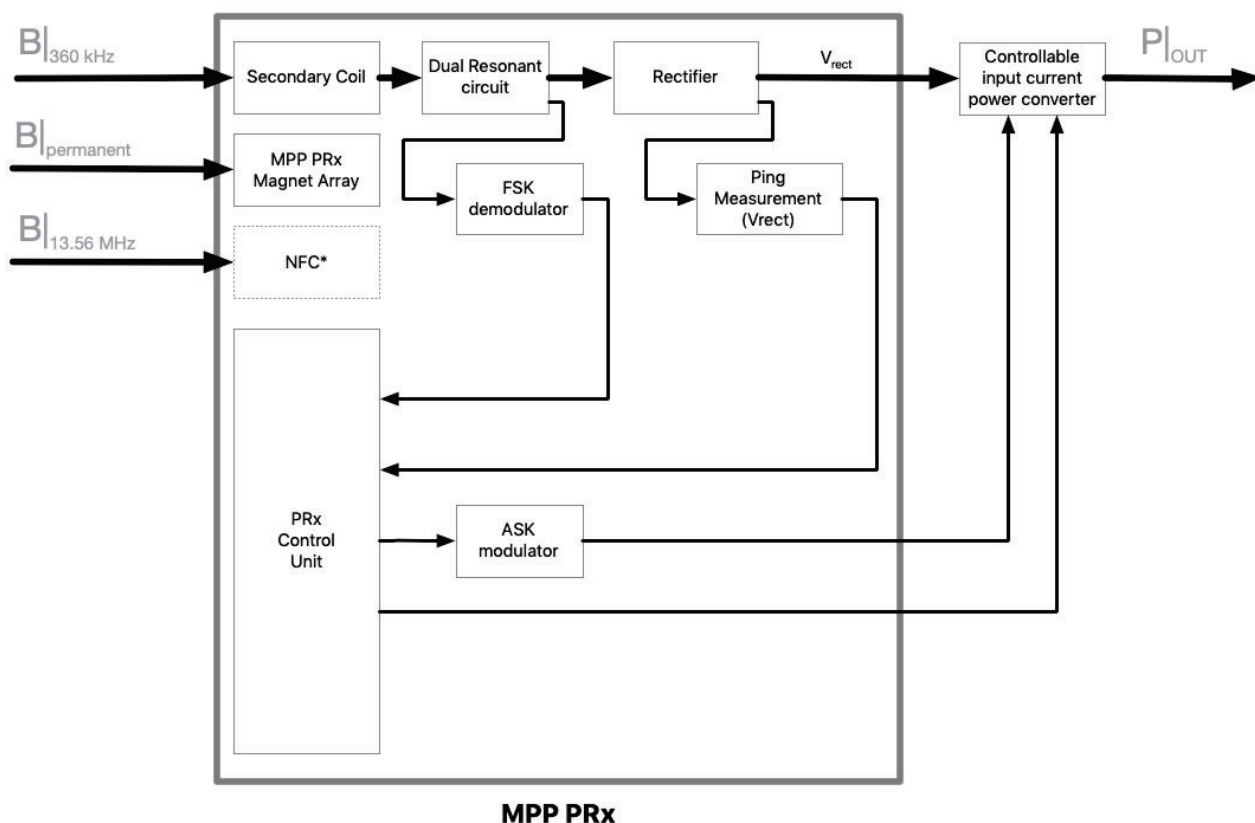


Figure 2.2.2: 5 MPP accessory functional diagram (e.g., PRx case, wallet, automotive dash-mount).



* Independent NFC applications can co-exist with MPP by interrupting power transfer. Same applies to the PTx (not shown in the picture).

Figure 2.2.2: 6 MPP PRx functional diagram.



1.3 Glossary

1.3.1 Definitions

Magnetic Power Profile (MPP): An extension to BPP that features magnets that guarantee tight alignment of the power transmitter and receiver, which enables safe power transfer up to 15W while also mitigating key fob interference

MPP power loss accounting (MPLA): An extension to power loss accounting (used in BPP), that uses a model of the physics of the wireless power system to improve accuracy. It enables the PTx and PRx to take temperature and the impact of friendly metal into account (i.e., compensate for these), with a large ecosystem in mind.

Extended Received Power Packet (PLA): The packet that an MPP PRx sends to an MPP PTx containing the received power and rectified power values

Open-Air Ping: The open-air Q test provides a method for detecting Foreign Objects placed on top of a Power Transmitter Product before a Power Receiver Product is brought into the Operating Volume. Refer to Annex B in the Foreign Object Detection book for further detail.

Sub Harmonic Oscillation (SHO): Oscillation at a sub-harmonic frequency of the operating frequency induced by saturation of the PRx ferrite.

System Model: A theoretical nominal implementation which functions as the basis for deriving requirements of compliant MPP PTx and PRx implementations.

2x2 cylinder: A cylinder with a radius of 2mm and a height of 2mm, from the center of the PTx coil. This cylinder is the magnet attach state-space and is used in Figure 4.3.2.1: 27 to define the 15W power delivery region. See § 5.1.3.1 for the definition of z and r used for this cylinder.

1.3.2 Acronyms

Term	Meaning	Comment
PTx	Power Transmitter	
PRx	Power Receiver	
TPT	Test Power Transmitter	
TPR	Test Power Receiver	

1.3.3 Symbols

Symbol	Name	Comment
V _{in}	PTx Inverter Input DC Voltage	
f _{op}	PTx Inverter Switching Frequency	
D	PTx Inverter Duty Ratio	
θ	PTx Inverter Phase Shift	θ=0° means the full-bridge inverter is operating in complementary mode. See § 5.3.1.1 Definition of inverter phase θ.
V _{inv}	PTx Equivalent Inverter Voltage	Equivalent inverter voltage that considers the inverter phase shift and duty cycle. See § 5.9.4.1.
V _{rect}	PRx rectified DC output voltage	
L _{TX} and L' _{TX}	The inductance of PTx coil module when it's in open air (L _{TX}) or when it's mated with a PRx (L' _{TX})	
L _{RX} and L' _{RX}	The inductance of PRx coil module when it's in open air (L _{RX}) or when it's mated with a PTx (L' _{RX})	
R _{TX} and R' _{TX}	The resistance of PTx coil module when it's in open air (R _{TX}) or when it's mated with a PRx (R' _{TX})	
R _{RX} and R' _{RX}	The resistance of PRx coil module when it's in open air (R _{RX}) or when it's mated with a PTx (R' _{RX})	

K_i	Inductive coupling factor	It's an unitless quantity between 0 and 1. Mutual inductance then is equal to $K_i \sqrt{L_{TX} L_{RX}}$
K_r	Resistive coupling factor	See § 8.4 Resistive Coupling Factor for the definition of K_r and explanation of why it's needed

1.4 System Model vs Spec

In the rest of the MPP System Spec book, we will go through different subsystems that together ensure a safe and efficient power delivery experience in MPP.

In general, most sections include the following subsections:

- System Model: this subsection describes the system model design for this subsystem. It is not required but can be used as a reference design.
- Specifications: this subsection (or a set of subsections) includes the specifications that MPP device shall meet.

Some sections only have the system model description but no specs. This indicates that the corresponding subsystem is not required (but recommended).

2 Authentication Protocol

2.1 Authentication

Introduction

An MPP PTx shall implement Authentication to provide tamper-resistant identity of its:

- Qi certification (Qi ID number).
- Manufacturer name (PTMC value).

Specifications

Refer to the books "Qi v2.0 Authentication Protocol" and "MPP Communications Protocol".

3 Coil Design

3.1 Introduction and Background

This section describes the MPP Tx and Rx coil system models.

The coil system models are nominal designs from which the MPP specifications are derived.

It is recommended that MPP PTx or PRx implementations follow these coil system models as closely as possible to minimize the differences with the TPT#MPP1-coil and TPR#MPP1-coil compliance test tools.

Each of the coil system model sub-sections are split into two sections:

- Mechanical specification of the individual components, full assembly, and materials.
- Nominal electrical parameters in free-air and mated conditions.

The final sub-section specifies the coil requirements for PTx and PRx implementations.

3.2 PTx Coil System Model

3.2.1 Mechanical Construction

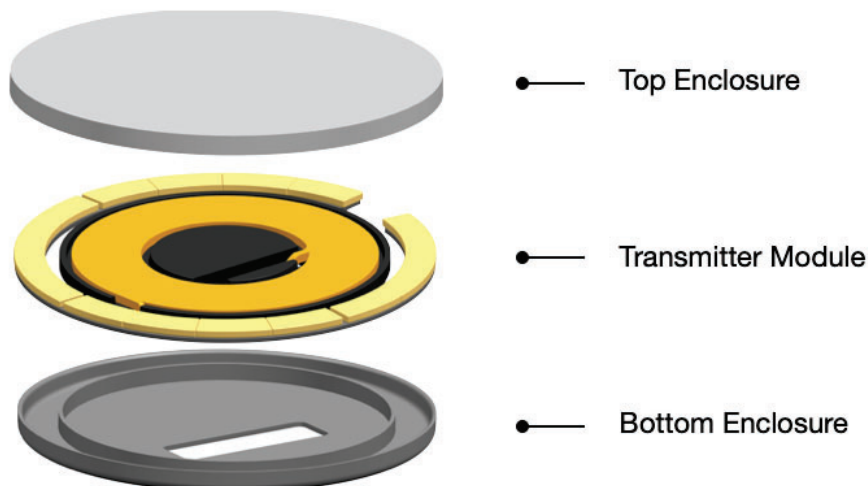
3.2.1.1 Overview

The overall design of the PTx coil system model is shown in Figure 4.2.1.1: 7 .

It consists of three main components:

- a top enclosure that defines the interface surface
- a coil module
- a bottom enclosure

Figure 4.2.1.1: 7 Exploded view of PTx coil system model.



3.2.1.2 Top Enclosure

The top enclosure is constructed with plastic.

3.2.1.3 Coil Module (AC magnetics)

The exploded view of the coil module for the PTx coil system model is shown in Figure 4.2.1.3: 8 . The coil module consists of four components:

- circular wound coil
- ferrite shield
- magnet ring
- permeable magnet shunt

The side view of the coil module is shown in Figure 4.2.1.3: 9 .

The coil is 11 turns constructed with Type-1 Litz wire with each turn consisting of 65 strands of individually insulated 80µm diameter copper wire.

The magnetic shielding in the coil module is constructed using DMR95 ferrite.

The purpose of the magnets is to ensure tighter alignment between the transmitter and receiver coils.

Practically, a cutout in the PTx ferrite is needed to allow the external routing of the coil leads. In Figure 4.2.1.3: 10 , the implementation of the ferrite cutout in the system model is shown.

Key mechanical dimensions of the coil module are in Table 4.2.1.3: 1 .

Figure 4.2.1.3: 8 Exploded view of the Coil Module for the PTx Coil System Model.

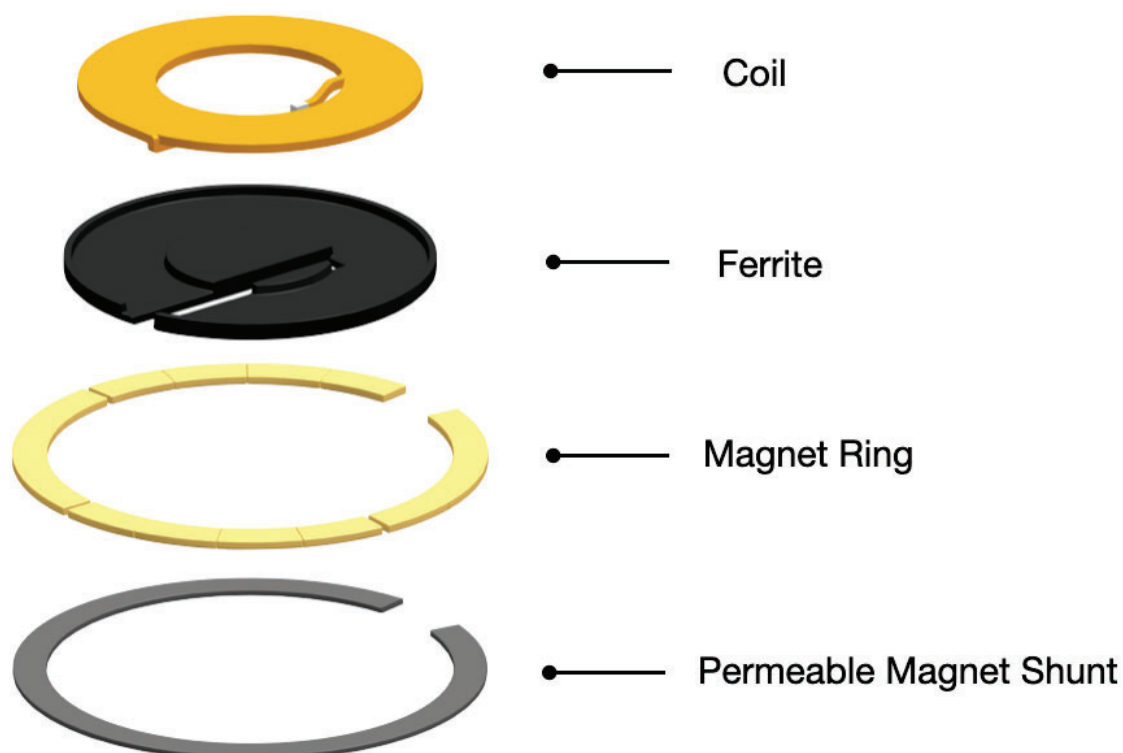


Figure 4.2.1.3: 9 Side view of PTx Coil Module.

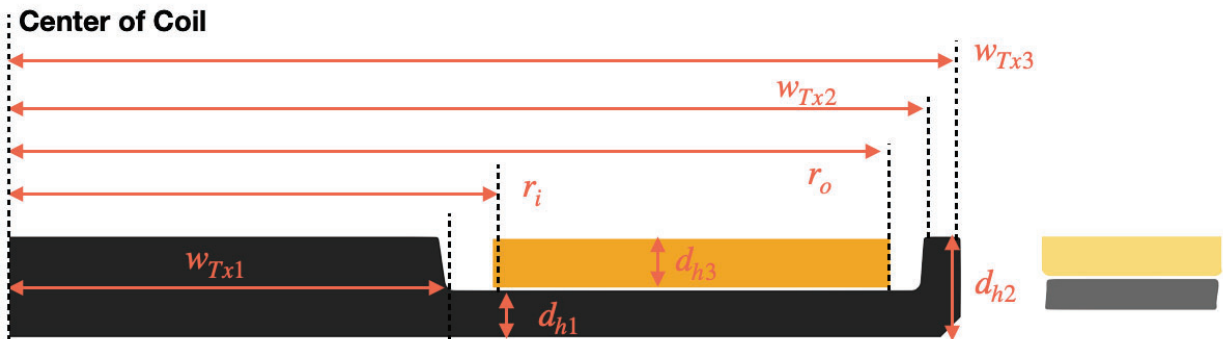


Figure 4.2.1.3: 10 Top view of PTx ferrite.

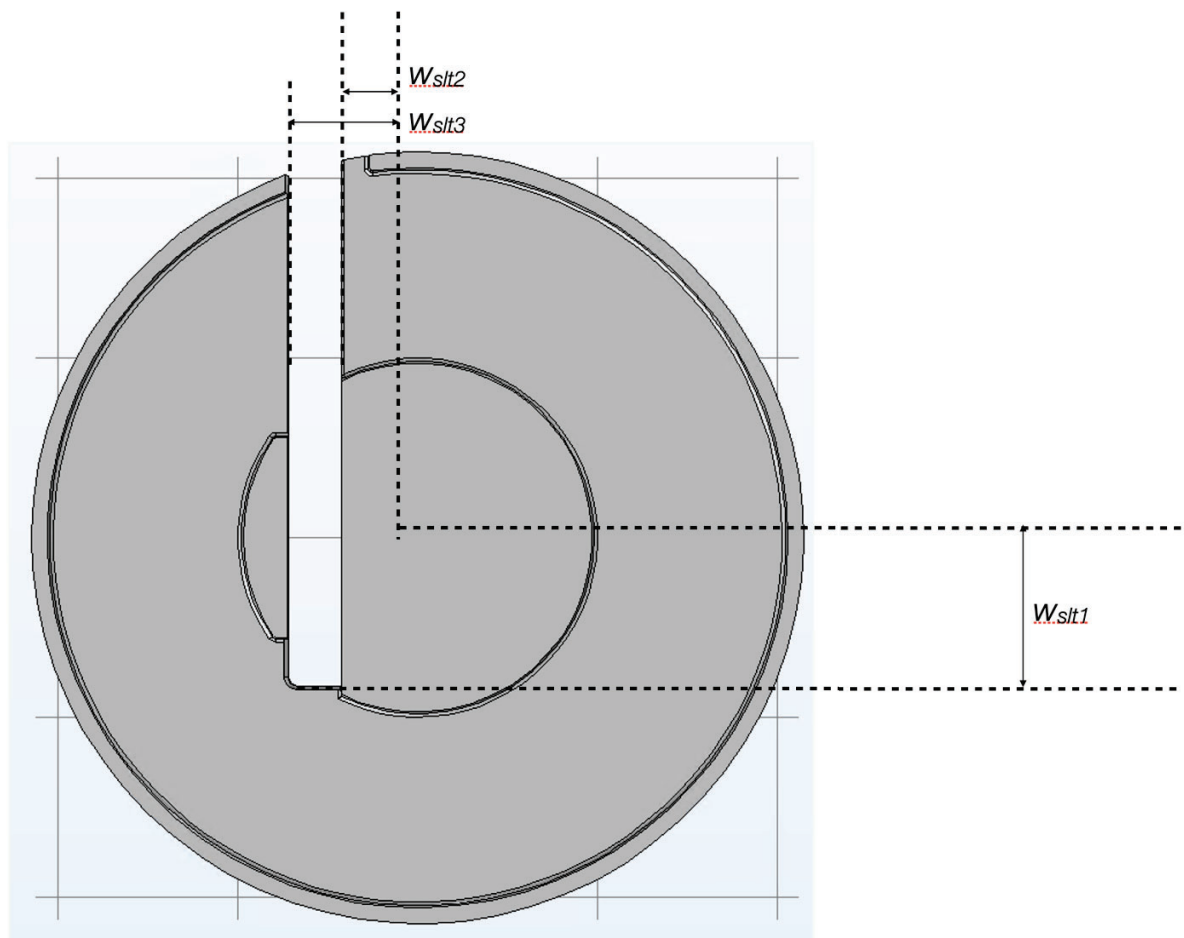


Table 4.2.1.3: 1 Mechanical dimensions for the coil module of the PTx coil system model.

	Description	Nominal Value
r_i	Inner radius of transmitter coil	10.73 mm
r_o	Outer radius of transmitter coil	19.65 mm
w_{Tx1}	Radius of ferrite center post	9.58 mm
w_{Tx2}	Inner radius of ferrite outer post	20.33 mm
w_{Tx3}	Outer radius of ferrite outer post	21.20 mm
d_{h1}	Thickness of ferrite base	1.15 mm
d_{h2}	Overall thickness of ferrite	2.15 mm
d_{h3}	Thickness of transmitter coil	1.03 mm
w_{slt1}	Vertical offset of ferrite cutout slot	8.20 mm
w_{slt2}	Horizontal offset of ferrite cutout slot	4.18 mm
w_{slt3}	Horizontal offset of outside edge of ferrite cutout slot	7.16mm

3.2.1.4 Coil Module (permanent magnets)

The magnet module consists of a permeable magnet shunt and magnets arranged in a circle around the coil module.

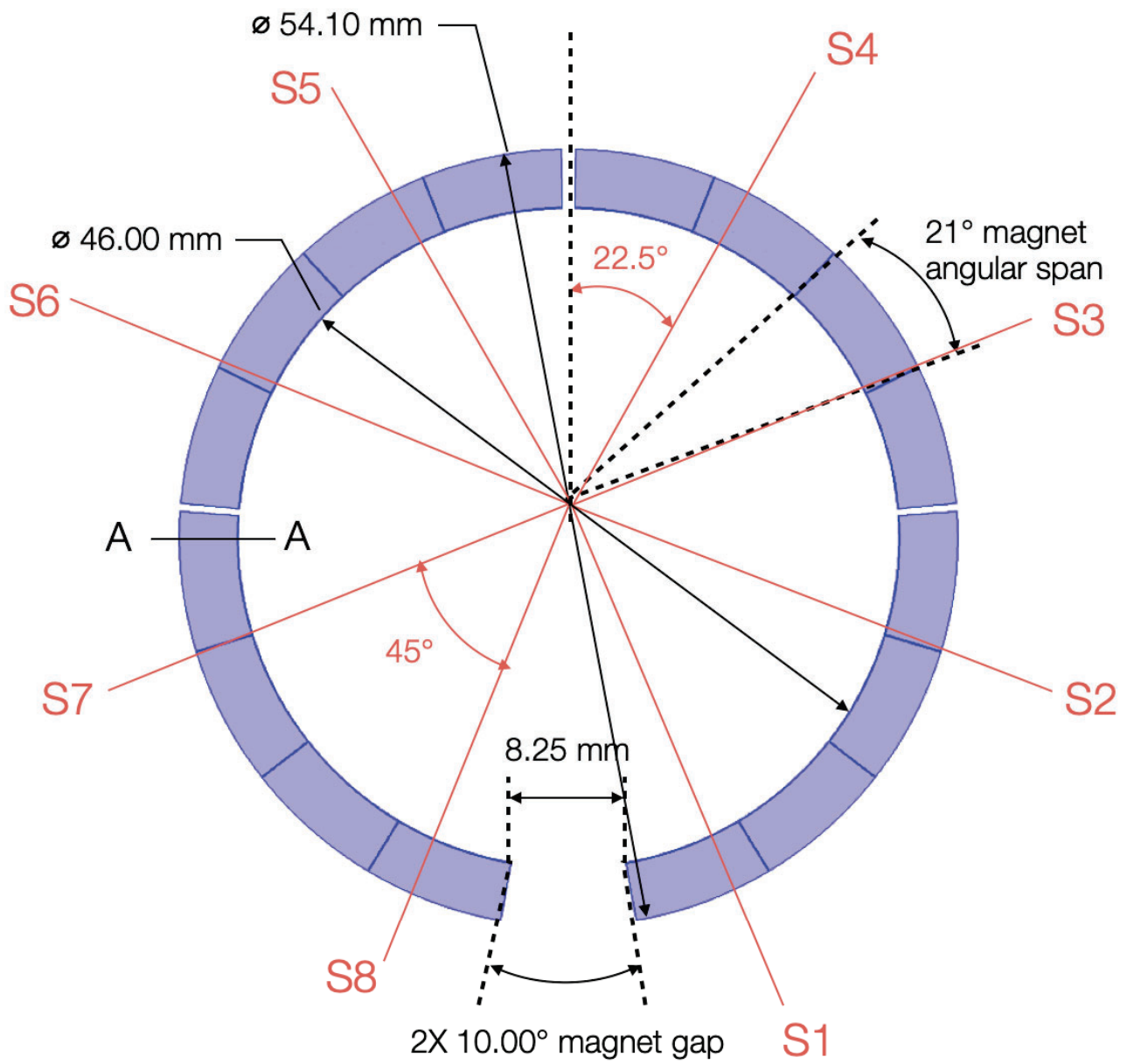
Details of the permanent magnet and shunt dimensions (shown in top view and cross-section view) are illustrated in Figure 4.2.1.4: 11 , § 4.2.1.5 Magnet shunt top view and Figure 4.2.1.5: 12 .

The dimensions and orientation (North or South) of the four poles in each magnet array element are essential for minimizing the impact on the AC magnetics. For the PTx system model, the B-field are measured in z- and xy-directions on the interface surface along S1-S8 as defined in Figure 4.2.1.4: 11 . The values of B-field thus measured are provided in Table 4.2.1.5: 2 .

The magnet array is constructed using NdFeB N48H grade magnets. The magnet array has a Ni-Cu-Ni plating layer of 10µm. The permeable magnet shunt is constructed with DT4. The material is chosen for high saturation flux density and high permeability. The key magnetic parameters of these materials are given here.

Component	Material parameter	Typical values
Magnet array	Br	1.39 T
	Hcb	$> 1.054 \times 10^6$ A/m
	Hcj	$> 1.353 \times 10^6$ A/m
	BHmax	3.7×10^5 T•A/m
Permeable shunt	Bsat	> 2.0 T

Figure 4.2.1.4: 11 Magnet Array top view.



3.2.1.5 Magnet shunt top view

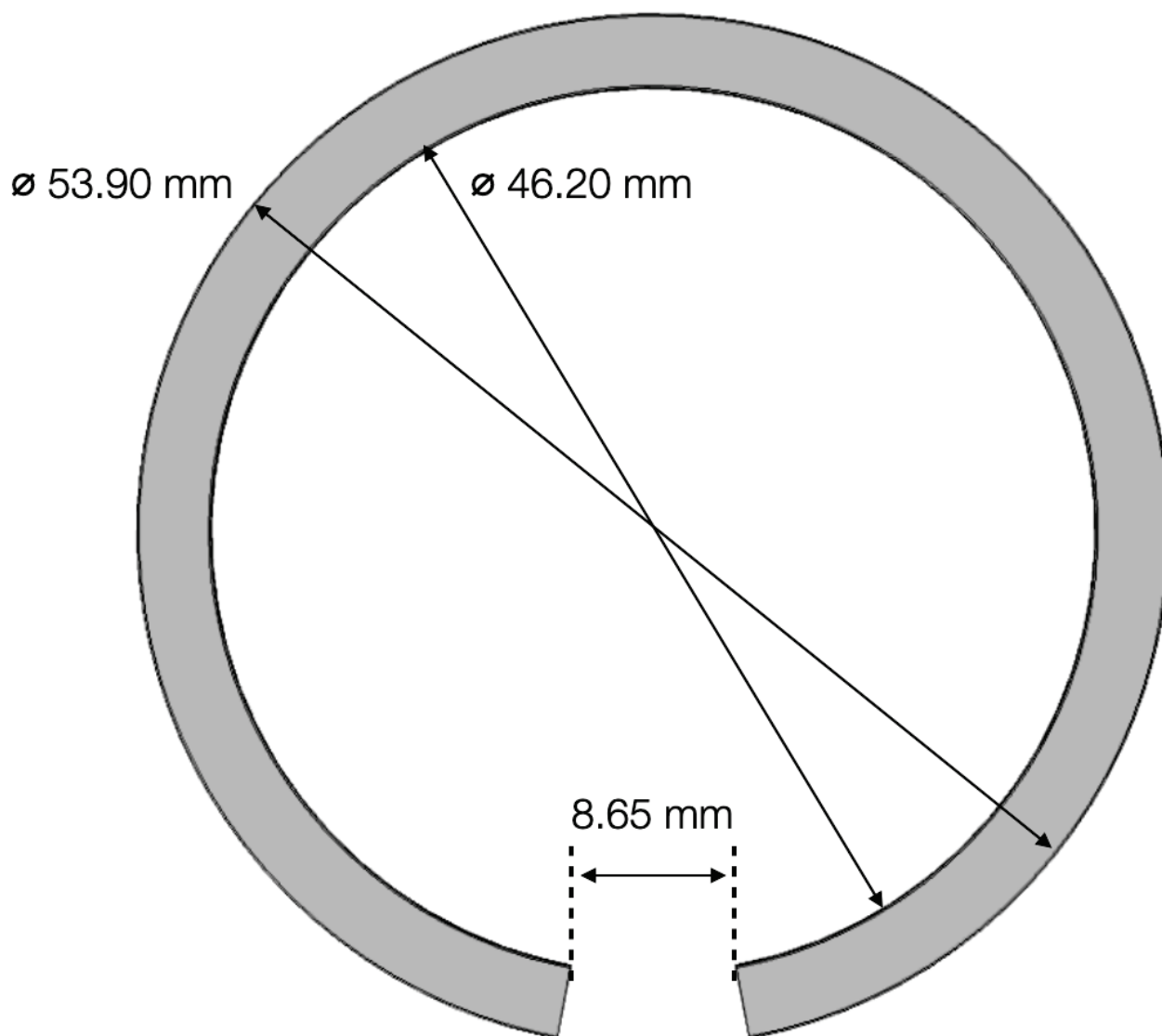


Figure 4.2.1.5: 12 Magnet assembly (Cross-section).

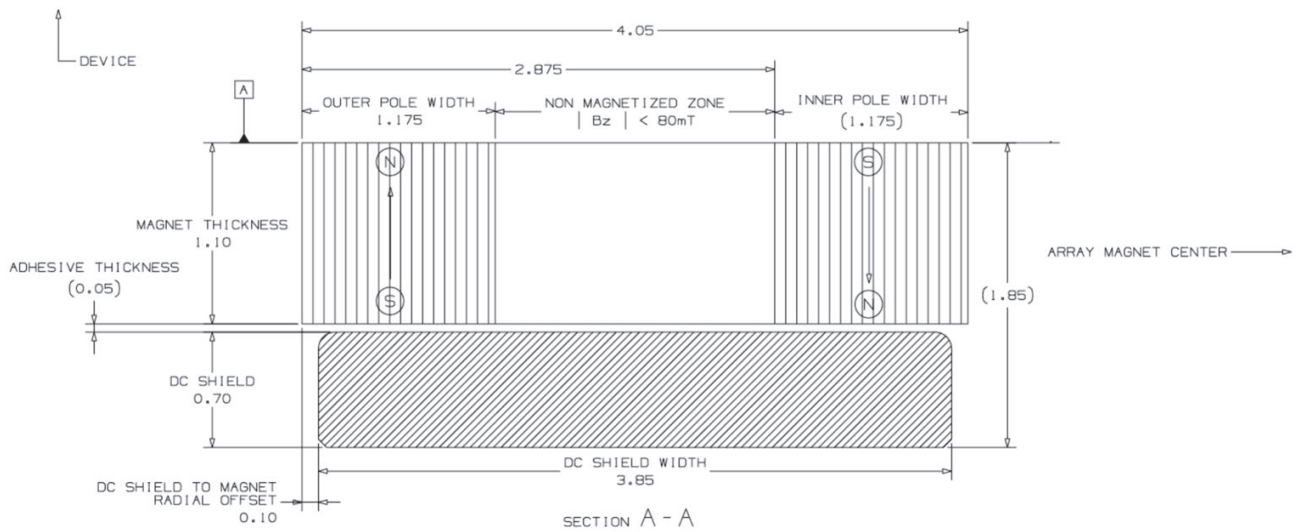


Table 4.2.1.5: 2 Magnetic field specifications for magnet array.

Radial Position (mm)	Bz (T)	Bxy (T)
$r < 19.5$	0	0.025
$19.5 < r < 23$	N/A	0.075
$23 < r < 24$	-0.185	N/A
$24.5 < r < 25.5$	N/A	0.1925
$26 < r < 27$	0.185	N/A
$27 < r < 30$	N/A	0.075
$r > 30$	0	0.025

* The $z=0$ plane refers to the interface surface, and $r=0$ refers to the center of the magnetic array.

3.2.1.6 Bottom enclosure

The bottom enclosure is made from 6061 grade aluminum. A cut-out is added to the bottom enclosure. This cutout is aligned with the ferrite cutout shown in Figure 4.2.1.3: 10 . This is to expose the coil leads and allow connection to external circuit. The dimension of the cutout is shown in § 4.2.1.7 Top view of bottom enclosure .

The cross-sectional and top view of the bottom enclosure is shown in Figure 4.2.1.6: 13 .

Mechanical dimensions of the bottom enclosure are specified in Table 4.2.1.7: 3

Figure 4.2.1.6: 13 Side view of Bottom Enclosure.



3.2.1.7 Top view of bottom enclosure

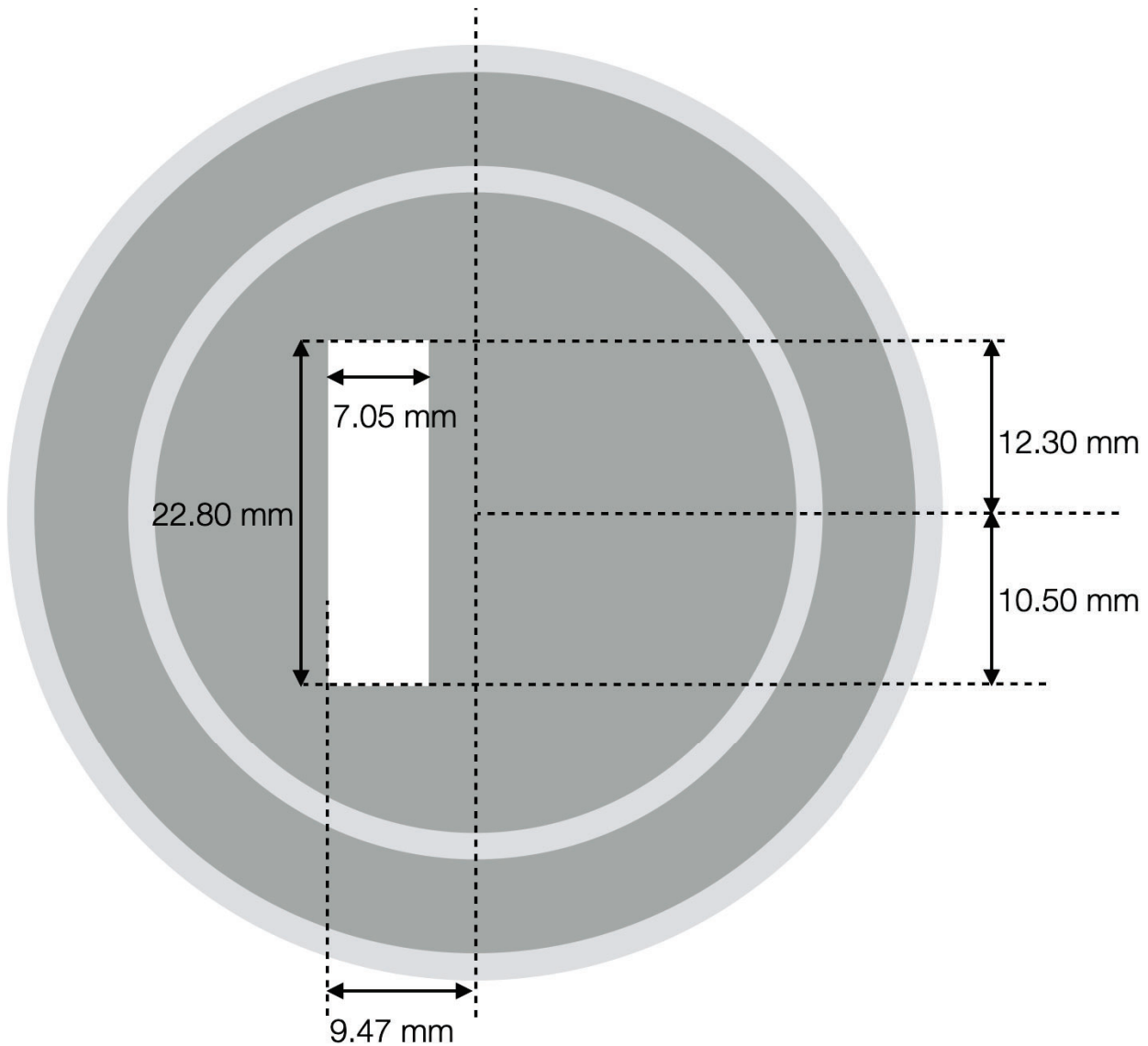


Table 4.2.1.7: 3 Mechanical dimensions for the bottom enclosure of the PTx coil system model.

	Description	Nominal Value
d_{enc1}	Bottom enclosure thickness	0.7 mm
d_{enc2}	Enclosure inner wall thickness	0.55 mm
d_{enc3}	Enclosure outer wall thickness	0.7 mm
d_{enc4}	Height of enclosure outer wall	3.25 mm
d_{enc5}	Height of enclosure inner wall	3.04 mm
w_{enc1}	Inner radius of enclosure inner wall	22.12 mm

W_{enc2}	Inner radius of enclosure outer wall	27.48 mm
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3.2.1.8 Overall Assembly

The assembly of the individual transmitter components described above is outlined below. A side view of the overall assembly of the reference transmitter is shown in Figure 4.2.1.8: 14. The description and specifications of the key dimensions of the reference transmitter assembly is given in Table 4.2.1.8: 4

Figure 4.2.1.8: 14 Side view of PTx coil system model assembly.

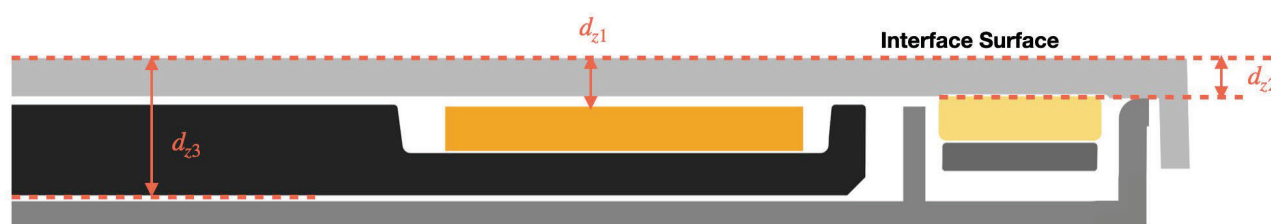


Table 4.2.1.8: 4 Assembly dimensions of PTx coil system model.

	Description	Nominal Value
d_{z1}	Distance from top surface of coil to interface surface	1.20 mm
d_{z2}	Distance from top of magnet surface to interface surface	0.95mm
d_{z3}	Distance from bottom of ferrite to interface surface	3.4mm

3.2.1.9 PTx Orientation Magnets

As discussed in previously sections, the magnet array in the PTx system model follow a ring shape around the coil module and therefore provides radial alignment between the transmitter and receiver coils but allows for rotation around the center of the magnet ring. To ensure the PTx and PRx only aligns in a particular angular direction, an "orientation magnet array" is added to the system model.

3.2.1.9.1 Transmitter-side Orientation Magnet

The top surface of the transmitter orientation magnet is in-plane with the main magnet array discussed in § 4.2.1.4 Coil Module (permanent magnets). The positioning of the orientation magnets with respect to the main magnet array is shown in Figure 4.2.1.9.1: 15, wherein the orientation magnet is labeled "clocking magnets". The center of the orientation magnet is aligned with the center of the magnet ring of the PTx coil system. The cross-section of the orientation magnet is shown in Figure 4.2.1.9.1: 16. The DC shield used in the orientation magnet should use the same material as the DC magnet shunt used in the main magnet array. The B-field strengths in z- and xy-direction are shown in Table 4.2.1.9.1: 5.

Figure 4.2.1.9.1: 15 Transmitter orientation magnets (Top View).

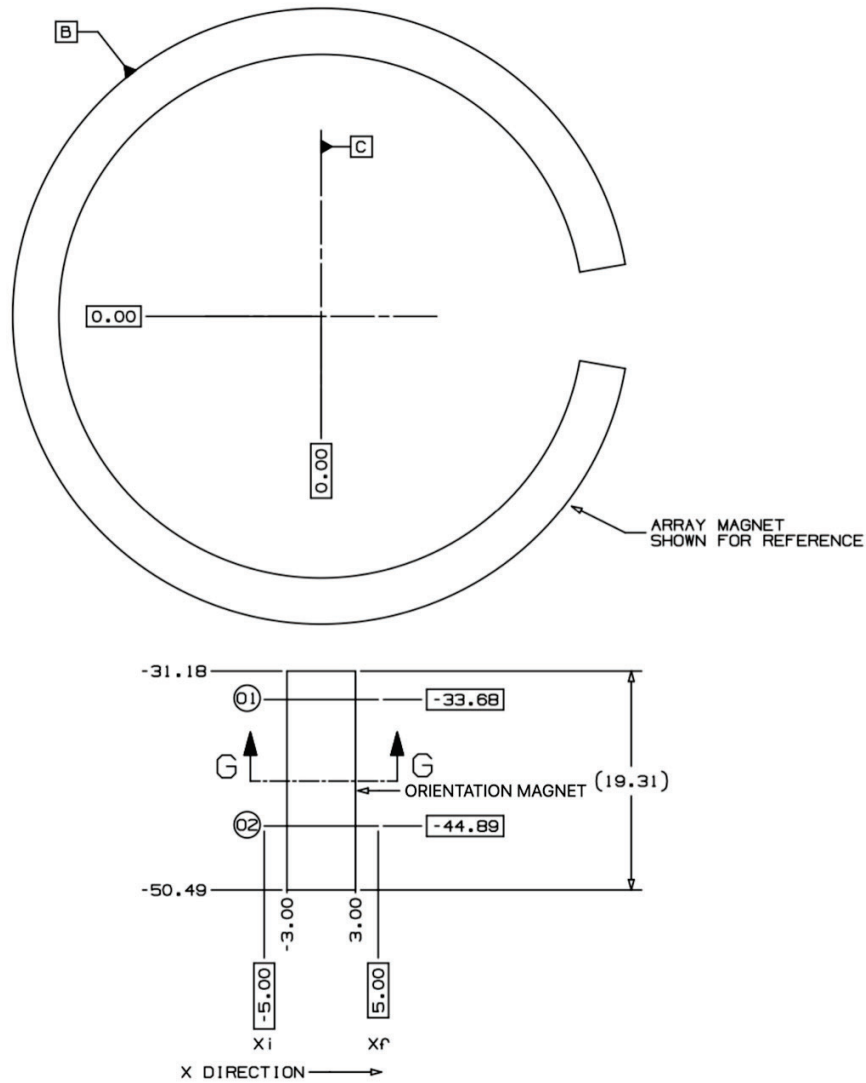


Figure 4.2.1.9.1: 16 Transmitter Orientation Magnet Dimensions and Polarity.

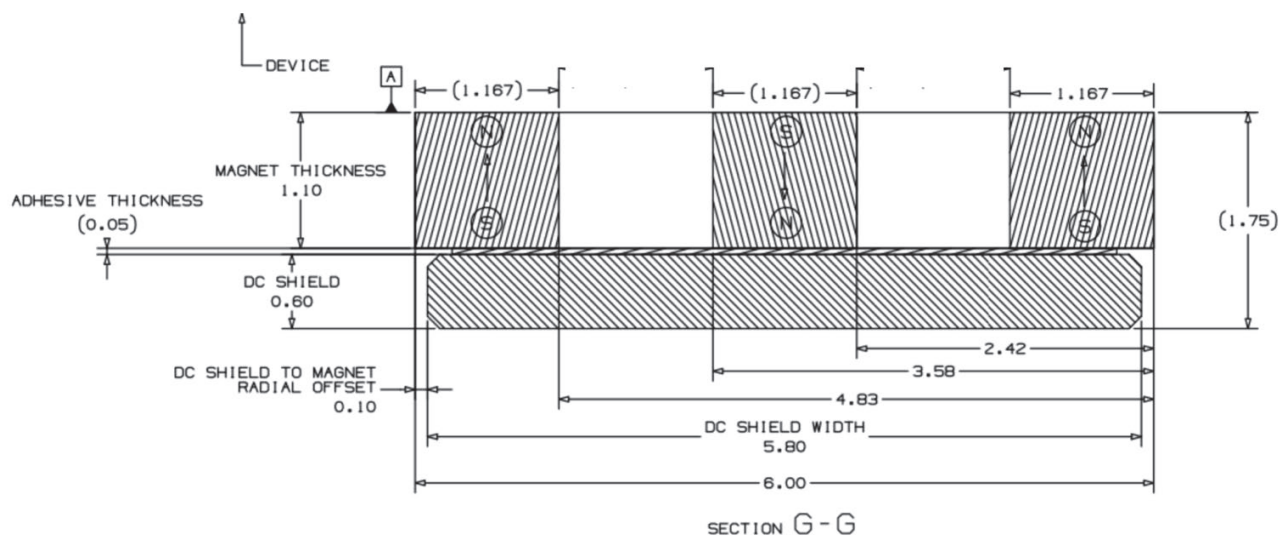


Table 4.2.1.9.1: 5 Flux density at 0.85mm from PTx orientation magnet surface.

Maximum x	Minimum Bz	Bxy
$x < -5.0$ mm	0	0.025
-5.0 mm $< x < 4.5$ mm	0	N/A
-4.5 mm $< x < -3.0$ mm	N/A	0.075 T
-3.0 mm $< x < -2.0$ mm	0.170 T	N/A
-2.0 mm $< x < -0.5$ mm	N/A	0.190 T
-0.5 mm $< x < 0.5$ mm	-0.250 T	N/A
0.5 mm $< x < 2.0$ mm	N/A	0.190 T
2 mm $< x < 3.0$ mm	0.170 T	N/A
3.0 mm $< x < 4.0$ mm	N/A	0.075 T
4.0 mm $< x < 5.0$ mm	0	N/A
$x > 5.0$ mm	0	0.025

* The $z=0$ plane refers to the interface surface, and $x=0/y=0$ refers to the center of the magnetic array.

3.2.2 Electrical Properties

3.2.2.1 Electrical Parameters of PTx coil system model

When the mechanical components are assembled as specified above, the PTx coil system model has the electrical parameters described in Table 4.2.2.1: 6 .

These values are valid under free-air conditions where there is no metallic or magnetic object present in the vicinity of the PTx.

Table 4.2.2.1: 6 Electrical Parameters of the PTx Coil System Model in Free-Air.

	Measurement Frequency	Description	Nominal Value
R_{DC}	N/A	DC resistance between coil terminals of the PTx coil system model	41 mΩ
L_{TX}	360kHz	Self-inductance between coil terminals of the PTx coil system model	7.42 μH
R_{AC}	360kHz	AC resistance between coil terminals of the PTx coil system model	260 mΩ

3.2.2.2 Preventing Saturation of PRx Shielding

The presence of magnets in an MPP PTx induces a DC bias flux in the Shielding of a PRx unit.

For proper operation, the magnetic Shielding must be operated in the non-saturated part of their B-H curve, away from their magnetic saturation inflection point.

Proper power delivery will be impeded if the Shielding of a PRx is allowed to saturate. For typical nano-crystalline (NC) Shielding materials, the saturation flux density is greater than 1T.

The risk of saturation is defined with reference to the TPR#MPP3, which is identical to TPR#MPP1 in all ways except that the number of nanocrystalline layers have been reduced to 3.

This makes TPR#MPP3 more sensitive to strong magnetic fields and a better candidate to evaluate the risk of PRx shielding saturation due to the PTx magnets.

For MPP, there is a risk of saturation if either of the following are true:

$$\Delta L'_{TPR\#MPP3_{(0,0)}} < 0.2$$

$$\Delta L'_{TPR\#MPP3_{(2,2)}} < -0.3$$

Where $\Delta L'_{TPR\#MPP3_{(0,0)}}$ is the normalized change of inductance of TPR#MPP3 when it is placed directly and in the center of the PTx (r=0mm, z=0mm).

$$\Delta L'_{TPR\#MPP3_{(0,0)}} = \frac{L'_{TPR\#MPP3_{(0,0)}} - L_{TPR\#MPP3_{Free Air}}}{L_{TPR\#MPP3_{Free Air}}}$$

And $\Delta L'_{TPR\#MPP3_{(2,2)}}$ is the normalized change of inductance of TPR#MPP3 when it is placed with a radial offset of 2mm from the center of the PTx and a 2mm spacer is present between the TPR and PTx. (r=2mm, z=2mm).

$\Delta L'_{TPR\#MPP3_{(2,2)}}$ is the minimum value when measured in all four directions e.g. (X, Y,Z) = (0,2,2), (0,-2,2), (2,0,2) and (-2,0,2).

$$\Delta L'_{TPR\#MPP3_{(2,2)}} = \frac{L'_{TPR\#MPP3_{(2,2)}} - L_{TPR\#MPP3_{Free Air}}}{L_{TPR\#MPP3_{Free Air}}}$$

The rationale of using $\Delta L'$ to detect saturation is as follows: under normal, unsaturated scenarios, $\Delta L'$ is positive as the ferromagnetic material on PTx helps to increase the inductance of PRx. But if the dc magnet saturates the PRx shielding (e.g., nano-crystalline shielding), then it effectively neutralizes the positive effect on PRx inductance brought by the shielding material and thus $\Delta L'$ will reduce. Additionally, the metallic material in PTx will also reduce $\Delta L'$ through the eddy-current effect. The compound effect will bring $\Delta L'$ down to zero or even negative.

Since (2,2) position has more offset than (0,0), it generally may introduce my saturation, that's why $\Delta L'_{TPR\#MPP3(2,2)}$ is smaller than $\Delta L'_{TPR\#MPP3(0,0)}$

3.3 PRx Coil System Model

3.3.1 Mechanical Construction

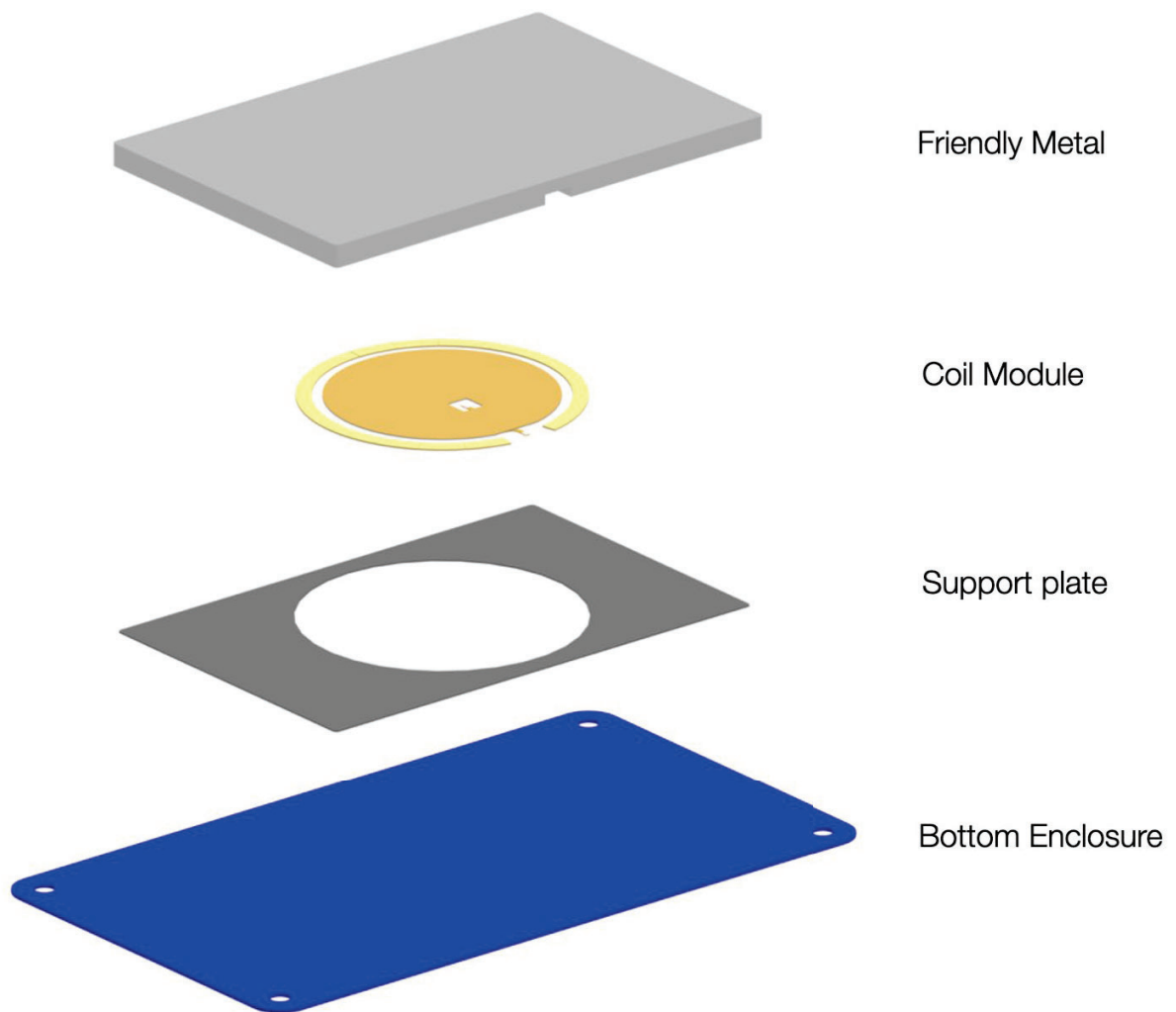
3.3.1.1 Overall Assembly

The overall design of the PRx coil system model is shown in Figure 4.3.1.1: 17 . It consists of four main components:

- bottom enclosure that defines the interface surface
- metal support plate
- coil module for wireless power transfer
- metal structure above the coil module defined as a “friendly-metal block”

In Figure 4.3.1.1: 17 the “friendly-metal block” is opaque, to denote that it is not intended to be part of a "real-world" PRx design (but its inclusion in the PRx coil system model is critical in ensuring interoperability). More details regarding the “friendly-metal block” are provided in § 4.3.1.6 Friendly Metal Block .

Figure 4.3.1.1: 17 Exploded view of PRx coil system model.



3.3.1.2 Bottom Enclosure

The bottom enclosure is constructed using glass.

3.3.1.3 Support Plate

The support plate of the PRx System Model is constructed using 6061 aluminum. The mechanical dimensions of the support plate can be found in Table 4.3.1.7: 11 .

3.3.1.4 Coil Module

The coil module of the PRx coil system model consists of four components:

- copper shielding
- magnetic shielding
- coil
- magnet array

An exploded view of the receiver coil module is shown in Figure 4.3.1.4: 18 .

A cross-sectional view of the coil module is shown in Figure 4.3.1.4: 19 .

The copper shielding aids to decouple the magnetic parameters of the PRx coil module from other system modules that may be present behind the coil module. Additionally, it also aids to minimize coexistence issues between the inductive charging system and other system modules.

The magnetic shielding in the PRx coil system model consists of a base layer and a center post. The base layer is constructed by stacking 7 layers of circular nano-crystalline sheets above the PRx coil. The center post is constructed by stacking 4 layers of nano-crystalline sheets. The specifications for the mechanical dimensions of the Shielding can be found in Table 4.3.1.4: 7 .

Figure 4.3.1.4: 18 Exploded view of the coil module for the PRx coil system model.

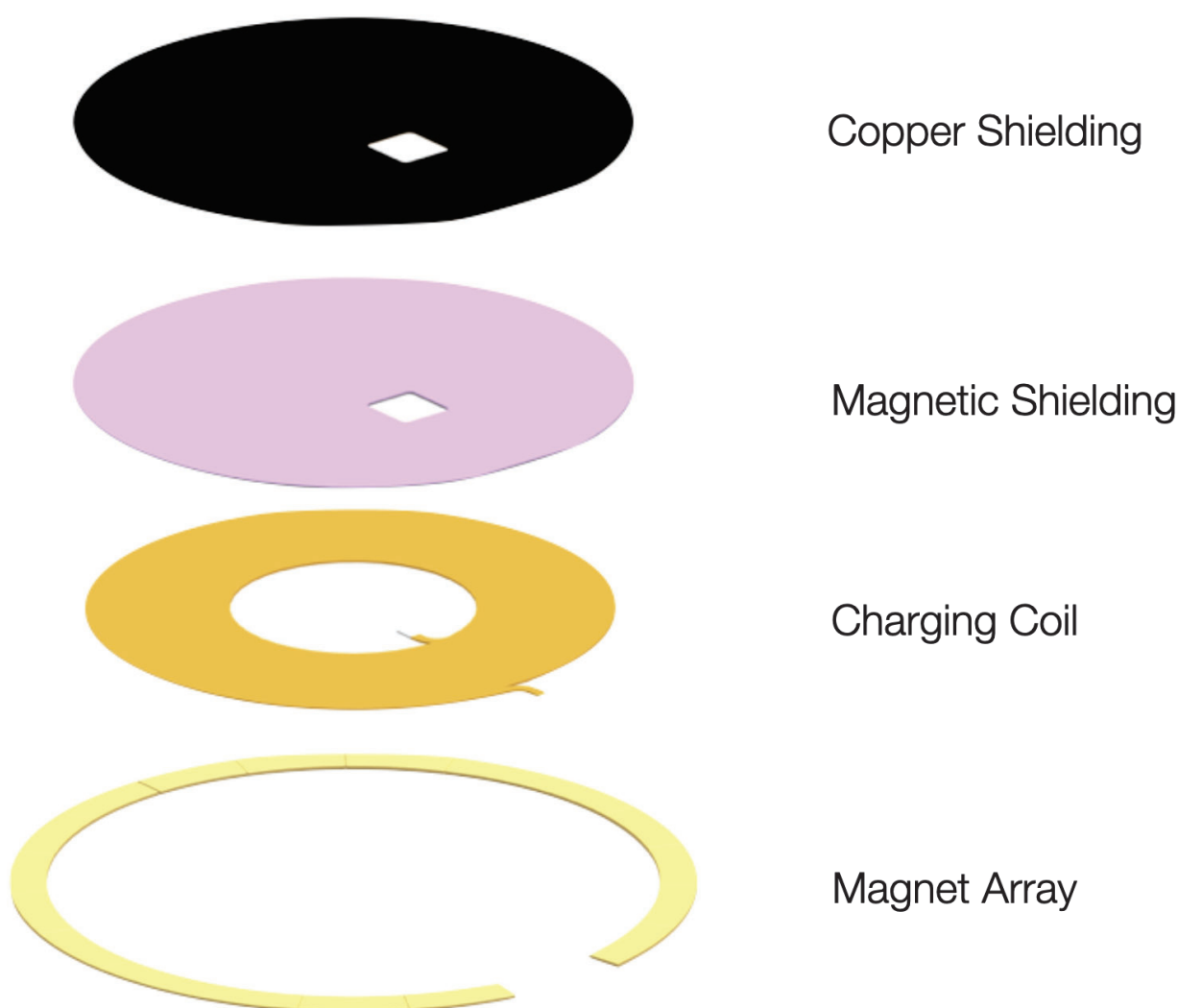


Figure 4.3.1.4: 19 Cross-section of the coil module for the PRx coil system model.



Table 4.3.1.4: 7 Assembly specifications of coil module for the PRx coil system model.

	Description	Nominal Value
w_{Rx1}	Radius of Shielding center post	8.95mm
w_{Rx2}	Radius of Shielding base layer	21.60mm
w_{Rx3}	Radius of Cu shield	21.60mm
d_{Rx1}	Center post shielding material thickness	80µm
d_{Rx2}	Base layer shielding material thickness	179 µm
d_{Rx3}	Cu shielding material thickness	30µm

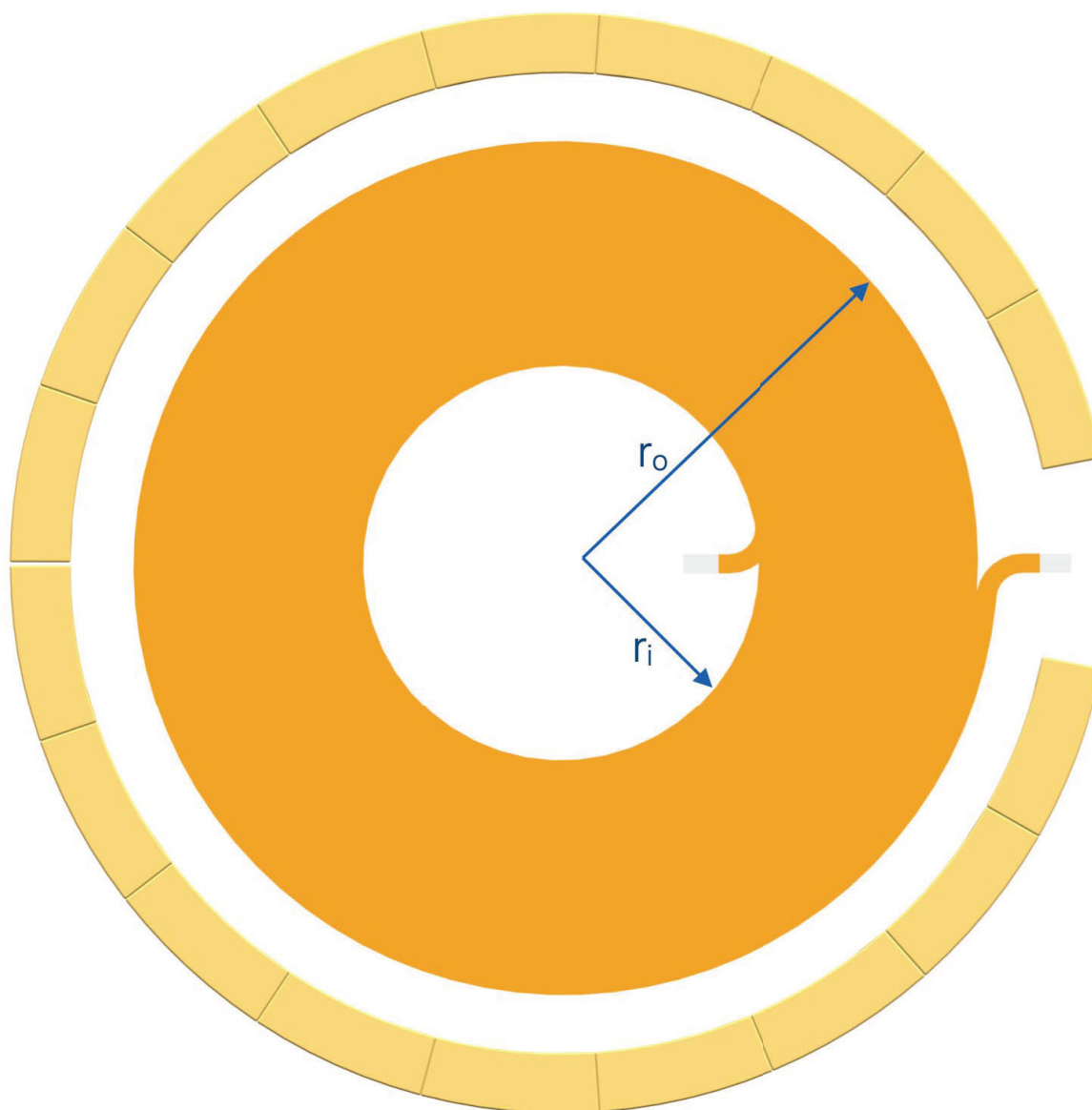
The top and cross-sectional view of the PRx coil system model is shown in Figure 4.3.1.4: 21 and Figure 4.3.1.4: 20, respectively. The receiver coil consists of a 1-layer of copper wires wound in 13 turns. To facilitate access to the coil terminals in practical designs, a cut-out exists in the Shielding to expose the coil leads. As shown in Figure 4.3.1.4: 21, one edge of the cutout is aligned with the geometric center of the Shielding. The mechanical dimensions of the PRx coil can be found in Table 4.3.1.4: 8.

Figure 4.3.1.4: 20 Cross-sectional view of coil for the PRx coil system model.

This diagram shows one turn with multiple strands in parallel. See Table 4.3.1.4: 8.



Figure 4.3.1.4: 21 Top view of PRx coil system model.



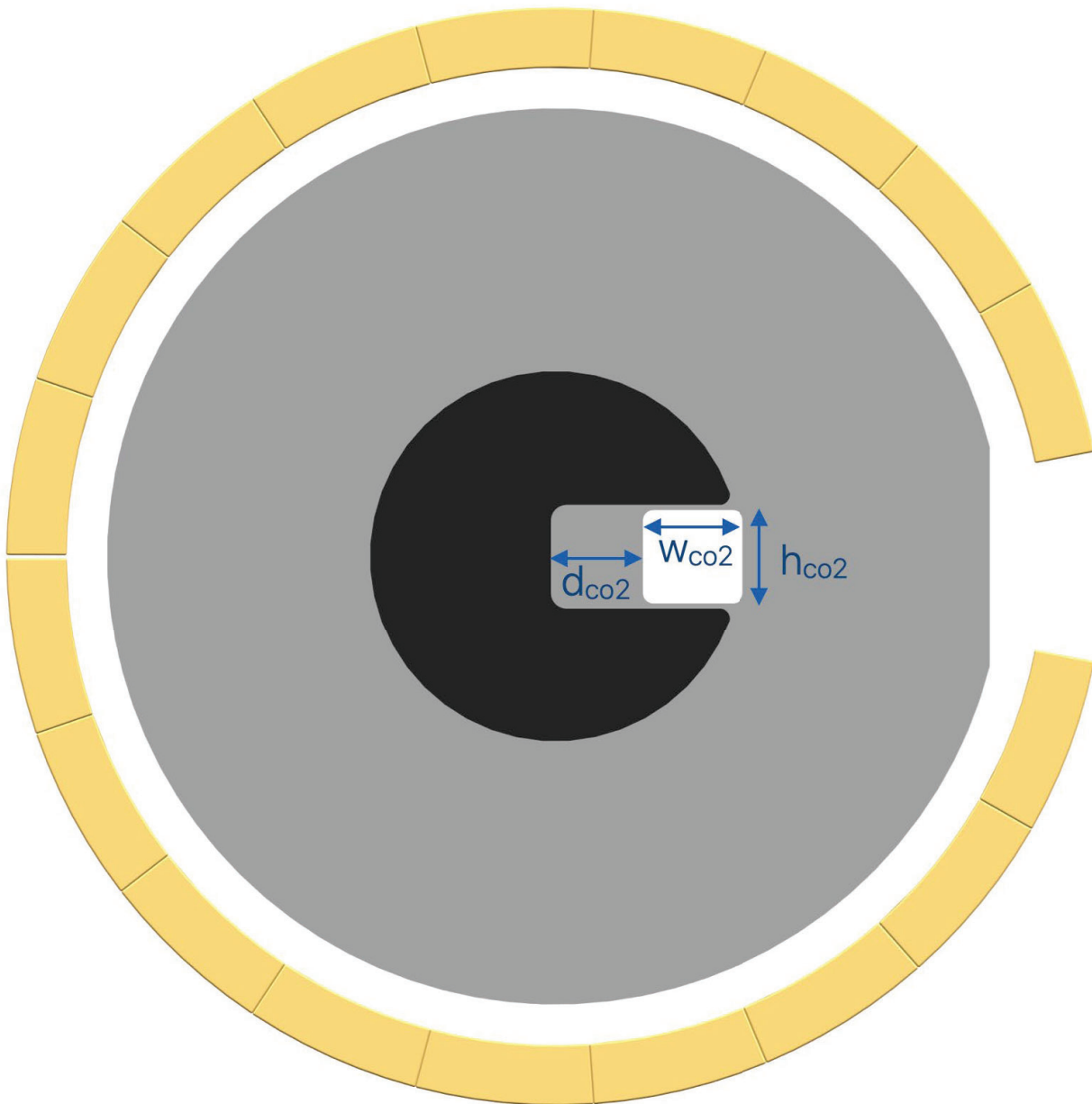


Table 4.3.1.4: 8 Mechanical specifications of the PRx coil system model.

	Description	Nominal Value
r_0	Outer radius of PRx coil	21.00 mm
r_i	Inner radius of PRx coil	9.50 mm
h_{co2}	Height of shielding cutout	4.50 mm
w_{co2}	Width of shielding cutout	4.85 mm
d_{co2}	Offset of shielding cutout from coil center	4.21 mm
w_{cl1}	Diameter of Cu Wire	114 μ m
w_{cl2}	Diameter of wire with insulation	131 μ m

N	Number of turns	13
N _c	Number of strands in parallel per turn (See Figure 4.3.1.4: 20)	7

3.3.1.5 Coil Module (permanent magnets)

Details of the magnet module dimensions are outlined in Figure 4.3.1.5: 22 , and Figure 4.3.1.5: 23 . The magnet module consists of magnet array elements arranged in a circle around the coil module.

The magnetic field values, as measured at the interface surface of the PRx Coil System Model, have been defined in Figure 4.3.1.5: 24 .

In Figure 4.3.1.5: 22 , an additional magnet (labeled "orientation magnet") is also included below the circular magnet array.

The orientation magnet assembly consists of a N48SH magnet and a thin shield above the magnet. The cross-sectional view of the PRx orientation magnet is shown in Figure 4.3.1.5: 25 .

The choice of materials for the construction of the permanent magnet module (including the circular magnet array and the orientation magnet) are outlined in Table 4.3.1.5: 9 .

Table 4.3.1.5: 9 Magnet properties of the PRx coil system model.

Component	Material parameter	Typical values
Magnet array	Br	1.39 T
	H _{cb}	> 1.054 x 10 ⁶ A/m
	H _{cj}	> 1.671 x 10 ⁶ A/m
	BH _{max}	3.7 x 10 ⁵ T•A/m
Permeable shunt	B _{sat}	> 2.0 T

Figure 4.3.1.5: 22 Magnet of the PRx coil system model (top view).

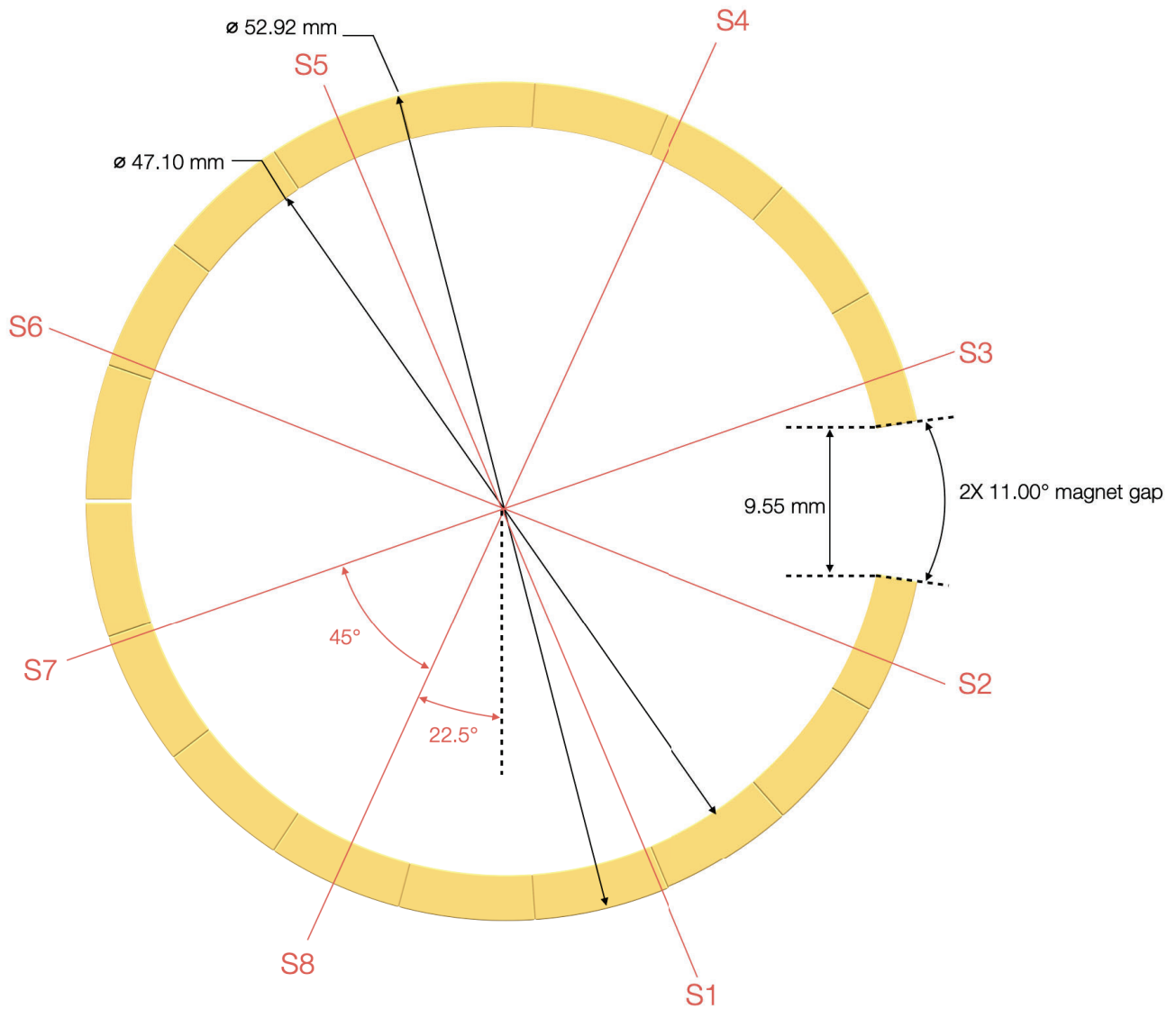


Figure 4.3.1.5: 23 Magnet of the PRx coil system model (side view).

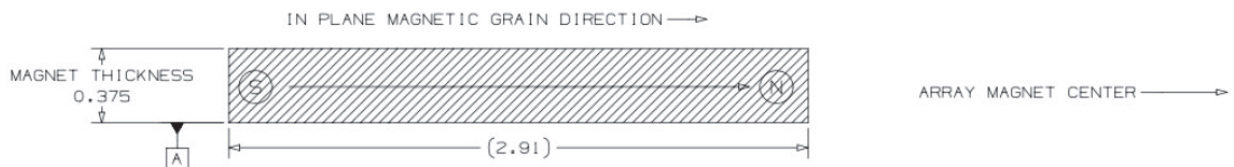
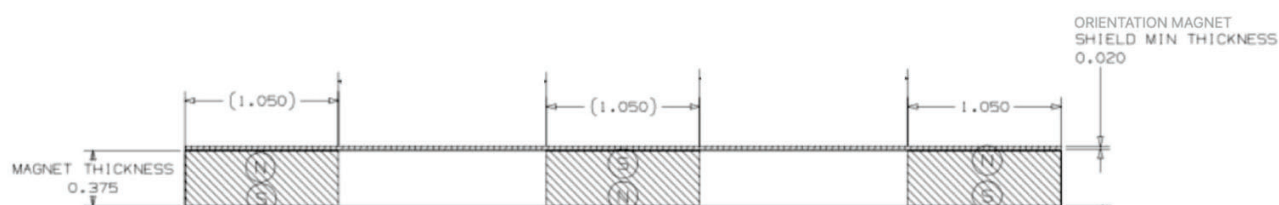


Figure 4.3.1.5: 24 Magnetic field of the PRx coil system model.

Radial Position (mm)	B _z (T)	B _{xy} (T)
$r < 19.5$	0	0.025
$19.5 < r < 23$	N/A	0.050
$23 < r < 24$	-0.0875	N/A
$24.5 < r < 25.5$	N/A	0.0825
$26 < r < 27$	0.0875	N/A
$27 < r < 30$	N/A	0.050
$r > 30$	-0.025	0.025

* The $z=0$ plane refers to the interface surface, and $r=0$ refers to the center of the magnetic array.

Figure 4.3.1.5: 25 Orientation magnet of the PRx coil system model (side view).



3.3.1.6 Friendly Metal Block

In a practical PRx implementation, it is likely that the coil module is surrounded by metallic components (such as battery, PCB), hereafter referred to as “friendly metal”. The friendly metal block shown in Figure 4.3.1.1: 17 is included in the PRx coil system model to represent such metallic components.

In the PRx coil system model, the friendly metal block is made from 316 grade stainless steel. The thickness of the friendly metal block is 4.30mm.

3.3.1.7 Overall Assembly

The assembly of the individual components of the PRx coil system model are outlined below.

A side view of the overall assembly of the PRx coil system model is shown in Figure 4.3.1.7: 26 . Description and dimensions of the assembly can be found in Table 4.3.1.7: 10 .

Figure 4.3.1.7: 26 Cross-sectional view showing assembly of PRx coil system model.



Table 4.3.1.7: 10 Assembly specifications for the PRx coil system model.

	Description	Nominal Value
d_{z1}	Distance from bottom of coil surface to Interface surface	0.660mm
d_{z2}	Distance from bottom of magnet surface to Interface surface	0.660mm
d_{z3}	Distance from bottom of support plate to Interface surface	0.700mm
d_{z4}	Distance from bottom of friendly metal block to Interface surface	1.23mm

Table 4.3.1.7: 11 Mechanical dimensions of support plate.

	Description	Nominal values
t_{SP}	Thickness of support plate	0.2 mm
r_{SP}	Radius of inner cutout of support plate	26.73 mm

3.3.2 Electrical Properties

3.3.2.1 Electrical Parameters of PRx Coil System Model

With the mechanical components assembled as specified above, the PRx coil system model has the electrical parameters described in Table 4.3.2.1: 12 .

These values are valid under free-air conditions. For the electrical parameters of the PTx coil system model when it is mated to the PRx coil system model refer to § 4.4 Properties of Mated Coil System Models .

Table 4.3.2.1: 12 Electrical Parameters of the PRx Coil System Model in Free-Air.

	Measurement Frequency	Description	Nominal Value
R_{DC}	N/A	DC resistance of the receiver measured at the coil terminals	200 mΩ
L_{RX}	360kHz	Self-inductance of the receiver measured at the coil terminals	9.01 μH
R_{AC}	360kHz	AC resistance of the receiver measured at the coil terminals	751 mΩ

3.4 Properties of Mated Coil System Models

3.4.1 Electrical measurement under mated conditions

The electrical parameters for the PTx and PRx coil system models under mated conditions are presented as a guideline for the design of compliant MPP PTx and PRx implementations. To this end, two cases are presented:

- In the first scenario, the PRx coil system model is placed directly on the surface of the PTx coil system model. This case (referred to as “z=0mm” test case), represents the nominal usage case where there is no spacing between the transmitter and the receiver and the two coils are aligned.
- In the second scenario, an air gap of 2mm is introduced between the PRx and PTx coil system models. This case (referred to as “z=2mm” test case), represents the usage scenario where a user may have an accessory attached to the PRx (e.g., a protective case) while charging.
- In both test cases, the PTx and PRx coils should be aligned (radial offset $r = 0\text{mm}$).

The electrical parameters to be measured under mated conditions include: L_{TX}' , L_{RX}' , R_{TX}' , R_{RX}' , K_i and K_r .

The description of these parameters and their expected values for both test cases are given in Table 4.4.1: 13 and Table 4.4.1: 14

Table 4.4.1: 13 Mated electrical parameters (Test case: $r=0$, $z=0$ mm).

	Description	Frequency	Nominal Value
L_{TX}'	Self-inductance at the coil terminals of the PTx coil system model	360kHz	14.80 μH
L_{RX}'	Self-inductance at the coil terminals of the PRx coil system model	360kHz	17.86 μH
R_{TX}'	AC resistance at the coil terminals of the PTx coil system model	360kHz	1.208 Ω
R_{RX}'	AC resistance at the coil terminals of the PRx coil system model	360kHz	1.938 Ω
K_i	Magnetic coupling between the PTx and PRx coil system models	360kHz	0.887
K_r	Resistive coupling between the PTx and PRx coil system models	360kHz	0.870

Table 4.4.1: 14 Mated electrical parameters (Test case: $r=2$, $z=2$ mm).

	Description	Frequency	Nominal Value
L_{TX}'	Self-inductance at the coil terminals of the PTx coil system model	360kHz	10.09 μH
L_{RX}'	Self-inductance at the coil terminals of the PRx coil system model	360kHz	12.09 μH
R_{TX}'	AC resistance at the coil terminals of the PTx coil system model	360kHz	0.630 Ω
R_{RX}'	AC resistance at the coil terminals of the PRx coil system model	360kHz	1.254 Ω