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INFINITE

Aerospace composites digitally sensorized
from manufacturing to end-of-life

D2.3 – Construction of the Portable Reader System
Gothenburg, 31th May 2025

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Version	**Date**	**Changes**	**Author**
0.1	02/10/2024	First version	RISE
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ABSTRACT / EXECUTIVE SUMMARY	
Abstract	This deliverable focuses on reporting on the construction of the portable reader. Three consecutive development stages of the high frequency portable reader are described as well as demonstrating the capabilities of the third one in terms of detecting microwires on the surface of carbon fibre composites. The third one, delivered to project partners, is reported in detail. Also, a low frequency version using magnetic fields capable of detecting microwires embedded in carbon fibre composites and accompanying software have been developed and delivered to project partners..
Keywords	MICROWIRES, MEASUREMENT SYSTEMS, DEMONSTRATORS. NDT

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This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

1. OBJECTIVE

Deliverable D2.3 is the output of the work done mainly in T2.3. Knowledge gained in T.2.1, T2.2. and the different tasks in WP1 is used as input. The deliverable consists of two functional portable readers optimized for reading magnetic microwires on and below the surface of carbon fibre composites ready for use in the following stages of the project.

The initial phase of the construction will be based on a commercial vector network analyser solution used at UPV, GAIKER and RISE. When the performance needed of the new portable reader is known a second, wholly INFINITE project optimized portable reader is to be constructed at 2.45GHz using development kits for various functions such as mixers, amplifiers and filters.

Once the function of that version is verified, a third version is to be designed based on the circuits used in the previous one. This version will be a fully custom-made portable reader including specifically for the INFINITE project designed printed circuit boards for transmitting and receiving the microwave signals as well as a custom-made power amplifier for generating a 100Hz magnetic field.

A low frequency portable reader is also to be developed to make sensing of microwires below the surface of carbon fibre composite structures possible.

As a part of the work software for controlling the portable reader as well as signal processing procedures will be developed. Different tests such as sensitivity to stress/strain will be performed. The knowledge gained in these tests will be input to the design of the signal processing procedures.

2. DESCRIPTION

In the following paragraphs the overall design strategy of the portable reader is outlined.

Initial reader based on a commercial network analyser [Leader RISE, UPV, TAM, IDK, TCE, CAE]

This part of the work consists of testing a newly developed cobalt rich microwire with better signal strength than previously as well as determine the direction of the microwires in relation to the carbon fibres. Integration and testing of signals from magnetic microwires in different carbon fibre coupons will be done. This part of the work will mainly use the vector analyser and the broad band antennas used in WP1 for characterization of the parameters of the magnetic microwires.

Second version based on development kits [RISE]

Furter development of the in WP1 proposed design of a transceiver using homodyne topology will be done. Optimization of the signal chain, i.e. magnetic coils, transmitting power, antenna selection, amplifier stages at microwave frequency as well as at baseband and analogue filtering will be done.

Third version using custom made PCBs [Leader RISE, IDK, UPV, USFD, GKR, TIT]

An optimized transceiver working at 2.45GHz will be designed and constructed. Using the knowledge from the previous version a homodyne-based transceiver will be made on a custom-built PCB. The transceiver will contain all circuitry for signal generation as well as signal reception and power management. The baseband output signals will be digitized and visualized on a computer.

Also, a custom-made low frequency amplifier for generation of the magnetic field is designed and constructed. The amplifier will be able to deliver enough current to safely generate a magnetic field larger than the magnetic coercivity of the magnetic microwires of choice.

When ready, portable readers will be delivered to partners. Training sessions will be provided by RISE to make the partners able to set up the equipment and use it correctly. Feedback from the partners will be used as input to further developments of the portable reader.

Further development of the portable reader [Leader RISE, UPV, IDK, USFD, GKR, TIT, CAE, TCE]

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Since microwaves and hence the backscattered signals from the magnetic microwires are heavily attenuated by carbon fibres, design of a portable reader using much lower frequency will be conducted. The low frequency version will also be more suited for industrial use since the antenna frontend will be a planar design enabling scanning of large surfaces. Using a low frequency system the integration of magnetic microwires do not need to be restricted to the surface of the carbon fibre structure, i.e. they can be integrated sub surface and hence make the overall integration process easier.

3. INITIAL READER BASED ON A COMMERCIAL NETWORK ANALYSER

The reader used in this phase of the development of the portable reader is based on vector network analyser for the transmission and reception of the microwave signals. The low frequency homogeneous magnetic field of about 80-130Hz was generated by a set of Helmholtz coils. The signal generator producing the low frequency signal was synchronized with the time sweeps of the vector network analyser. Before entering the Helmholtz coils the low frequency signal was buffered and amplified by a power amplifier

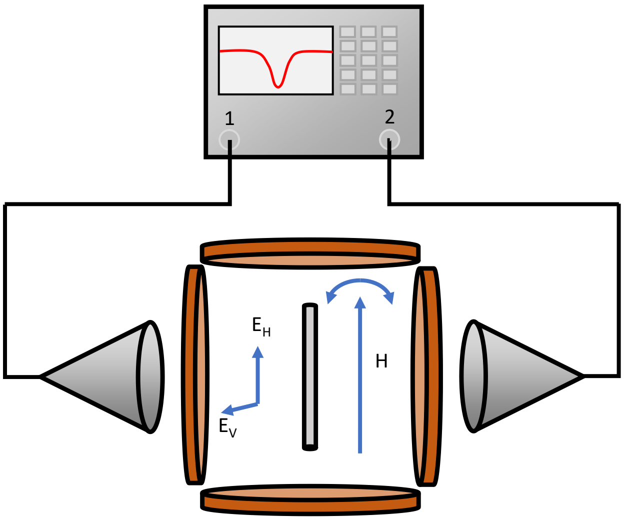

Figure 1 Schematic picture of the measurement set up when testing magnetic microwires of different compositions.

The complete list of equipment used in the RISE setup is listed in Table 1. UPV and Gaiker use the same vector network analyzer but have different prerequisites in terms of antennas and anechoic chamber.

EQUIPMENT	DESCRIPTION	MODEL
VNA	Two-port portable VNA (10kHz-20GHz)	Keysight Streamline, P5004B
Antennas	Two dual polarized 2-18GHz horn antennas	Flann Microwave, DP240-AB
Cables	Two 3m coaxial cables	Cinch RF Cable RG316
Helmholtz coil pairs	Two Helmholtz coil pairs 30cm diameter	3B Scientific, 1000906
Amplifier	Amplifier for the magnetic field	ACCEL instruments, TS250-2

Table 1 Equipment used at RISE for the initial phase of the portable reader development

3.1 MEASUREMENT OF MAGNETIC MICROWIRES WITH OPTIMISED COMPOSITION

The optimisation of the magnetic microwires were done jointly by Tamag and UPV/EHU in T.2.2. The newly developed magnetic microwire alloy is $Co_{72}Fe_4B_{13}Si_{11}$ with a metal core diameter of 40µm and an outer glass diameter of 45µm. Initial

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tests in T2.2 showed that the signal strength should be increased from the previously maximum GMI ratio of 280% to about 350%-600% depending of excitation frequency. Measurements made by RISE using the vector network analyser-based reader at 2.45GHz shows an increase in detected signal strength of about 900% with the new composition compared to the old one.

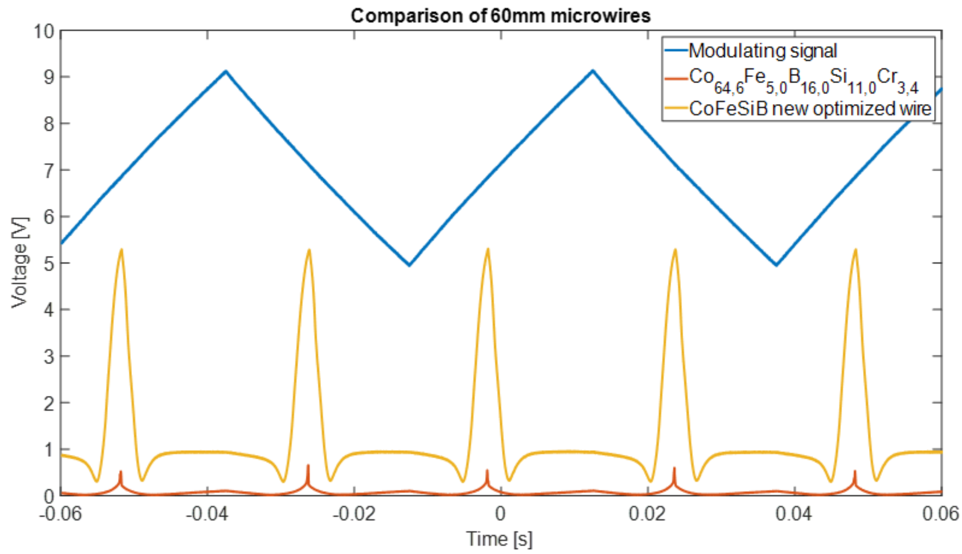

Figure 2 Comparison of signal strength of the new CoFeSiB based magnetic microwire compared to the previous CoFeBSiCr based one shows an increase of about 900% at 2.45GHz.

Measurements where the direction of carbon fibres in relation to the magnetic microwires were investigated. The result was that the magnetic microwires measured at 2.45GHz preferably should be oriented perpendicular to the carbon fibres. The worst combination was found to be when the magnetic microwires are in the same direction as the carbon fibres. A practical solution with sufficiently good signal strength was to place the magnetic microwires 45° in relation to the carbon fibres. Using the results from the measurements, an INFINITE-standard carbon fibre coupon was designed and manufactured by IDEKO. The standard coupon was called P2 and should be used by all project partners when comparing their portable reader set-ups. Since the signal strength from magnetic microwires placed inside carbon fibre structures it was decided that the magnetic microwires should be placed on one of the surfaces of the coupon. The coupon consists of four layers of ±45° oriented carbon fibres which gives the coupon a thickness of about 2mm. Length and width is 300mm and 50mm respectively. Four microwires spaced by 9mm were placed on the bottom surface.

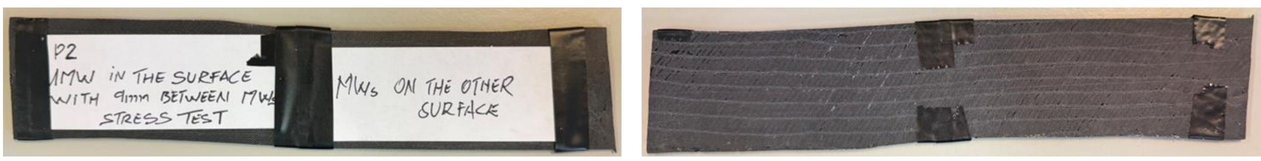

Figure 3 Front and back side of the P2 coupon. Four magnetic microwires with a spacing of 9mm are placed on the back side surface

Measurement of the backscattered raw signal using a spectrum analyser is shown in Figure 4. In the centre of the picture the carrier wave of 2.40 GHz is shown. To the left and right sidebands due to modulation of the impedance of the microwires are shown. The sidebands are approximately 40dB or 10000 times smaller than the carrier signal.

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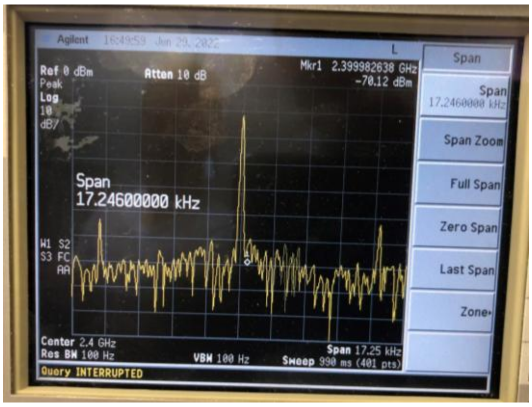

Figure 4 Spectrum analyser view of the raw backscattered signal from a P2-coupon at 2.4GHz. Carrier and sideband due to the modulation of the magnetic field are visible.

4. SECOND VERSION OF THE PORTABLE READER BASED ON DEVELOPMENT KITS

The second version of the portable reader is designed to use the free ISM-band around 2.45GHz. The use of that frequency band enables the use of a plethora of ready-made development kits from different semiconductor suppliers. This will decrease the overall development time considerably.

Figure 5 shows the schematic overview of the portable reader. A PC with suitable software (Digilent Waveforms, Matlab, LabView, Python etc) will control an Analog Discovery 3(AD3), a USB-C-connected mixed signal oscilloscope. The AD3 will generate the low frequency magnetic field signal of about 100Hz. The low frequency signal will be connected to a power amplifier before it will be connected to the Helmholtz coils. The AD3 will also receive the down converted 2.45GHz signals from the transceiver/RF-frontend section of the system and digitize them. The transceiver is connected to a 2.4GHz dual polarized WiFi-antenna which transmits signals in one polarisation and receives signals from the magnetic microwires in the other, thus measuring the S11 scattering parameter. A dual polarized antenna is used to reduce crosstalk and increase signal to noise ratio.

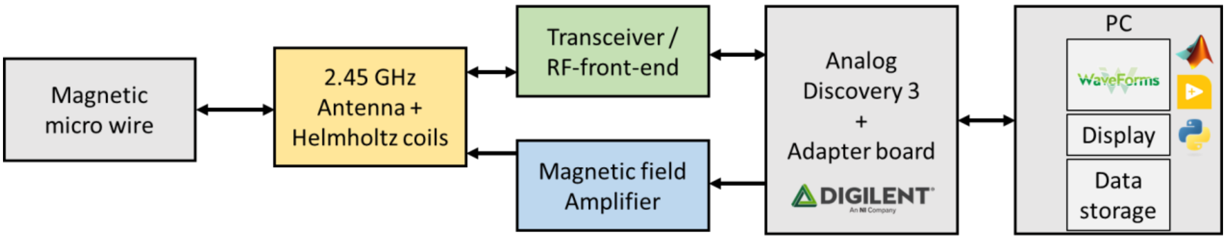

Figure 5 Schematic overview of the second version of the portable reader.

In this version of the portable reader, the power amplifier for the low frequency magnetic field is the TS250-2 from ACCEL instruments.

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Figure 6 5 Left: Power amplifier Middle: Helmholtz coils Right: Dual polarized Wi-Fi antenna

4.1 THE TRANCEIVER SECTION

After tests with different coupons and magnetic microwires a topology for the transceiver section was decided. The design maximises signal to noise ratio and sensitivity. The transceiver section, shown in Figure 7, is responsible for transmitting and receiving the 2.45GHz signals. A 2.45GHz signal is generated from a 100MHz reference signal source via a phase locked loop and a voltage-controlled oscillator. To reduce harmonic emission and spurious emissions a bandpass filter are placed after the PLL/VCO. To be able to control the output signal strength a steerable attenuator is inserted into the signal chain. After the attenuator the signal is amplified by a power amplifier before it is transmitted to the antenna. The design goal is to be able to reach, but not pass, +13dBm (20mW) to comply with the European RED directive. Measurements in the lab shows that maximum output power is +11dBm (12.5mW), which is acceptable since output power is not the limiting factor for the performance of the transceiver.

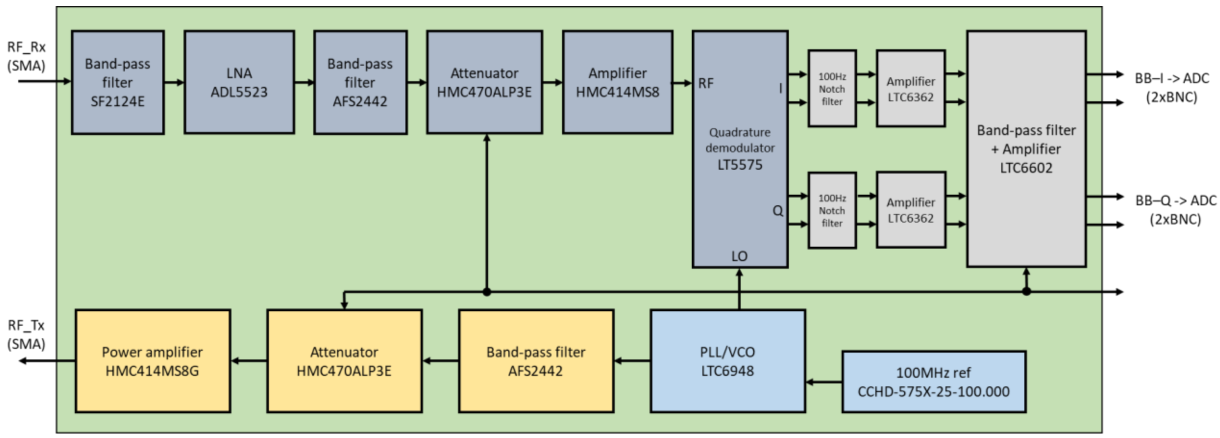

Figure 7 Schematic picture of the transceiver section of the second version of the portable reader.

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The backscattered received 2.45GHz signal is fed to a narrow band pass filter to reduce interference from other transmitting sources like microwave ovens, WiFi, Bluteooth, cell phones and such devices. After filtering a low noise amplifier and a second band pass filter is employed to the signal. Then a steerable attenuator(0-31dB) is inserted to enable attenuation of the received signal in the event of very high signal strength which otherwise will cause saturation and non-linear behaviour of the receiver chain which in turn will cause degradation of signal to noise ratio and sensitivity. Then the signal is fed to a quadrature direct down conversion IQ-demodulator. In the IQ-demodulator the received signal is multiplied with a small part of the transmitted signal. This will translate the received 2.45GHz signal to baseband centred around DC. The down converted baseband signals containing the response from the microwires are then amplified (steerable 0-30dB) and low pass filtered before digitalization.

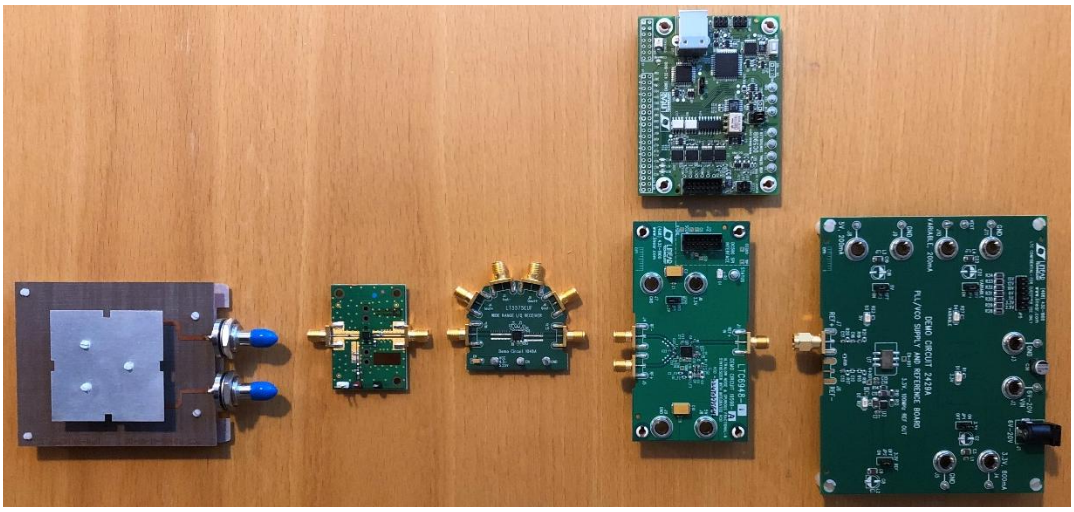

Figure 8 Most of the important parts of the transceiver section.

During the development of the second version of the portable reader online documentation and design files have been studied to understand recommended main component placement and layout of interfacing components.

No	Part number	Manufacturer	Description
1	ADL5523-EVALZ	Analog Devices	ADL5523 LNA board
2	105006-HMC414MS8G	Analog Devices	HMC414MS8G RF amplifier board
3	EV1HMC470ALP3	Analog Devices	HMC470ALP3E attenuator board
4	DC2429A	Analog Devices	LT3042 PLL/VCO supply and reference board
5	DC2491A	Analog Devices	LT3045 LDO regulator board
6	DC1048A	Analog Devices	LT5575 quadrature demodulator board
7	DC1833A	Analog Devices	LTC6362 differential amplifier board
8	DC1304A-A	Analog Devices	LT6602 bandpass filter board
9	DC1959B-A	Analog Devices	LTC6948-1 PLL with VCO board
10	DC590B	Analog Devices	LTC6948 USB serial controller board

Table 2 Evaluation boards used in the second version of the portable reader.

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5. THIRD VERSION USING CUSTOM MADE PCBS

The third version of the portable reader uses two custom made printed circuit boards, one for the high frequency section including low voltage power supplies and one for the low frequency magnetic field amplifier. In addition to the custom-made PCBs a Digilent Analog Discovery 3 is used a signal source for the Helmholtz coils and to digitize the received signals from the microwires.

5.1 THE TRANSCEIVER SECTION

The transceiver of the third version contains all the parts used in the version two plus additional low voltage power supplies for various ICs. The local oscillator used for generating the high frequency carrier in the 2.45GHz ISM-band is programmed by a serial communication interface (SPI) via a program[1] supplied by Analog Devices together with a programmer (DC590B).

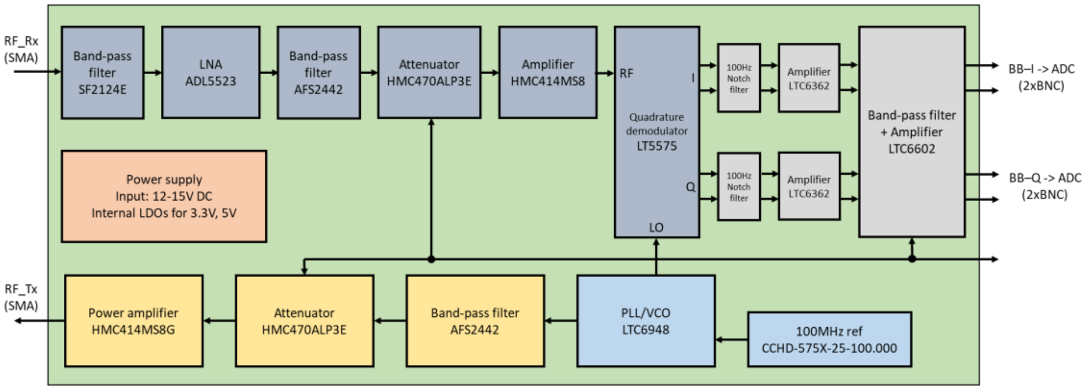

Figure 9 The transceiver section of the third version of the portable reader.

The PCB is made of a four-layer standard FR4 material. Schematics and layout of the transceiver is found in Appendix A – 2.45GHz transceiver schematics and layout.

[1] The program, Fraqnwizard can be downloaded from the Analog Devices homepage: https://swdownloads.analog.com/fracnwizard/fracnwizardsetup.exehttps://swdownloads.analog.com/fracnwizard/fracnwizardsetup.exe

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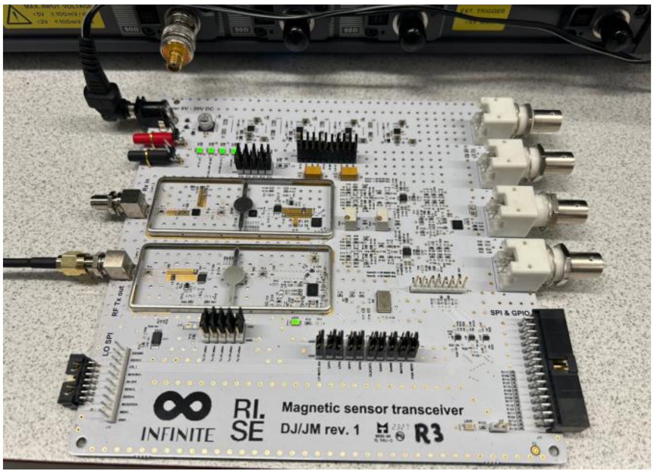

Figure 10 The transceiver circuit board during testing.

Figure 11 Front and back side of the transceiver box. High frequency input and output (Rx,Tx) and low frequency differential outputs (I+,I-,Q+,Q-) are visible as well as power input (6.5V) and programming interfaces (LO SPI, SPI & GPIO).

5.2 ADAPTOR CARD

The Analog Discovery oscilloscope and signal generator does need an adaptor card to interface the generated signals from and received ones to it. An adaptor card, based on the original one distributed by Digilent was designed and fabricated where two output channels are available as well as two balanced input channels, as opposed to the original one that housed single ended inputs. All analog input and output signal channels are accessible through BNC connectors. An additional 2x15 row pin-header makes trigger signals and digital input/output signals accessible as well.

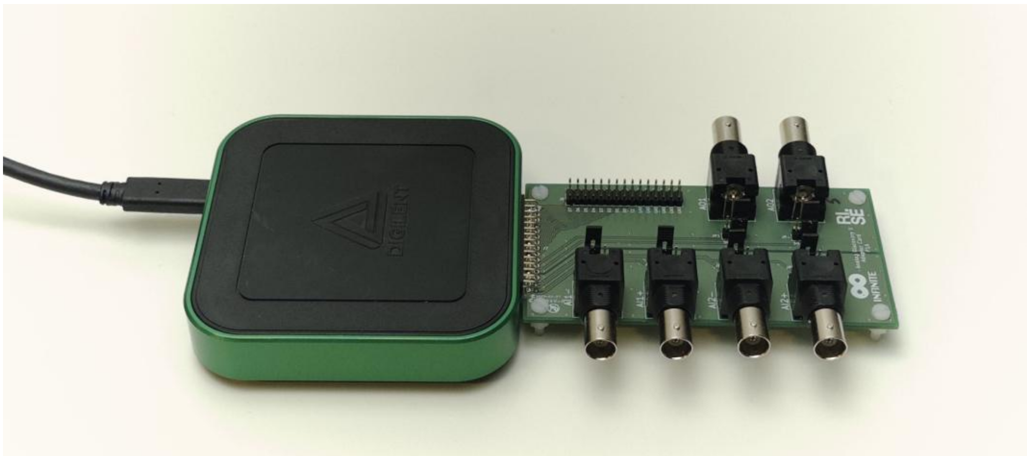

Figure 12 The adaptor card connected to an Analog Discovery 3 USB oscilloscope.

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The schematics of the adaptor card can be found in Appendix c - Adapter card Schematics and Layout

5.3 THE LOW FREQUENCY MAGNETIC FIELD AMPLIFIER

The low frequency magnetic field amplifier amplifies the output voltage from the Analog Discovery board so the Helmholtz coils can generate the required magnetic field strength necessary to excite the magnetic microwires. The design criteria were to have a linear gain of 10 (20dB) and to be able to generate minimum current of 1A at 1kHz. Preferably, but not a strict requirement the maximum bandwidth should be 100kHz.

The solution is built on a Texas Instrument operational amplifier, OPA541, capable of delivering up to 5A at supply voltages as high as ±40V. In this application where it is supposed to work as a current source to a pair of Helmholtz coils driven at a few hundred Hertz it is sufficient to deliver currents up to slightly above one Ampere.

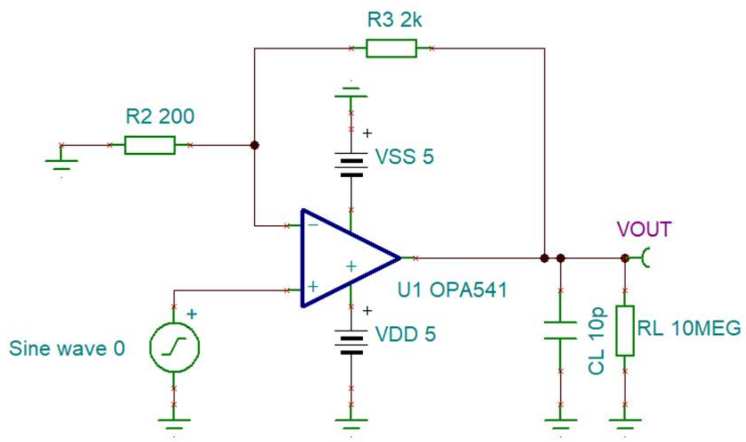

Figure 13 Schematic overview of the low frequency magnetic field amplifier

The amplifier is powered by ±20V using 2mm banana plug connectors. The input and output signals are connected by standard BNC connectors.

Figure 14 The low frequency magnetic field amplifier PCB mounted in an aluminium case.

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After fabrication the frequency response was measured and compared to specifications and simulations. The amplifier has a gain of 10 (20dB) up to 100kHz which is within specifications. The results show a lightly higher 3dB bandwidth than the simulation. The measurements and comparative simulations are shown in Figure 15.

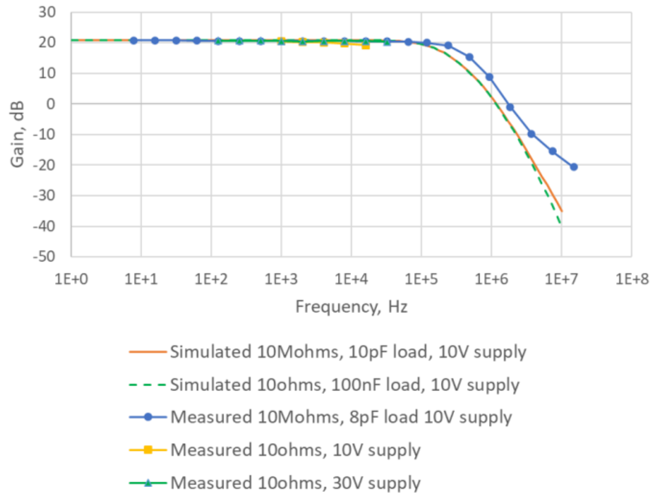

Figure 15 Simulated and measured gain of the magnetic field amplifier.

5.4 THE COMPLETE HIGH FREQUENCY SYSTEM HARDWARE

The high frequency portable reader system hardware that was used by RISE and partners consists of the items in Table 3. The RISE-manufactured items were delivered to the partners by RISE. All other items were procured by respective partner.

Row	Item	Quantity	Manufacturer	Manufacturers product number	Mouser	VWR	Distrelec
1	RF-frontend / Transceiver	1	RISE				
2	Current amplifier	1	RISE				
3	Signal Conditioning Board	1	RISE				
4	Ribbon cable 2x15pin	1	RISE				
5	Analog Discovery 3	1	Digilent	410-415	424-410-415		
6	Local Oscillator programmer	1	Analog Devices	DC590B	584-DC590B		
7	Helmholtz coils	1	3B Scientific	1000906		765-0599	
8	2.45GHz RX/TX-antenna	1	Huber-Suhner	1324.19.0056	455-1324190056		
9	RF-cable RG-316	2	Johnson / Cinch Connectivity Sol.	415-0029-M3.0	530-415-0029-M3.0		
10	Banana plug adaptor 2mm->4mm Red	1	RND	RND 350-00050			RND 350-00050
11	Banana plug adaptor 2mm->4mm Black	1	RND	RND 350-00051			RND 350-00051
12	Banana plug cable red 60in	2	Mueller Electric	BU-PB60-2	548-BU-PB60-2		
13	Banana plug cable black 60in	2	Mueller Electric	BU-PB60-0	548-BU-PB60-0		
14	BNC-BNC cable RG59 1m	5	RND	1222148			1222148
15	BNC-2xBanana plug cable 1.1m	1	RND	RND 350-00009			RND 350-00009

Table 3 Equipment list for the high frequency portable reader

5.5 SOFTWARE

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The Analog Discovery 3 USB based oscilloscope comes with a user interface program, Waveforms[2], to control all settings and features. RISE provided the partners with a so-called workspace file with all settings set to default values valid for the high frequency portable reader.

Setting	Value
Sampling frequency	400kHz
Number of samples	16k
Range ch 1 and 2	±2V
Modulation frequency	100Hz
Modulation voltage	2.2V
Low pass filter	Butterworth
Low pass filter order	4
Low pass filter cut-off frequency	20kHz

Figure 16 Main settings of the workspace.

It is possible to save data in CSV-file format using the Waveform program for later processing in other programs. It is also possible to stream raw data from the two input channels to a file for later processing.

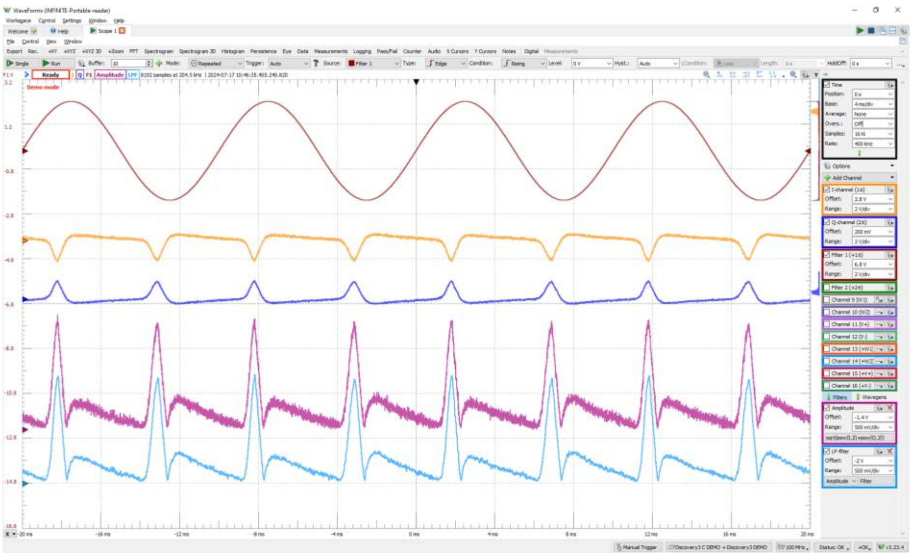

Figure 17 Screenshot from the distributed workspace for Waveforms used for the high-frequency portable reader.

5.6 TESTING OF THE THIRD VERSION OF THE HIGH FREQUENCY PORTABLE READER

All versions of the high frequency portable reader were tested with bare magnetic microwires as well as carbon fibre based coupons made by IDEKO. Bare magnetic microwires gave high back scattered signal strength with high signal to noise ratio (30-100 times or approximately 30-60dB). Already at first tests of carbon-based coupons with embedded magnetic microwires it was clear that the received signal strength from the magnetic microwires was very low. Synchronous reception of the signals from the magnetic microwires with the low frequency magnetic field of 100Hz helped to remove some of the background noise and scattered signals from the surroundings when using averaging. However, the signal to noise ratio was too low to be used in a real-world setting, even with very low demands on acquisition time. Also, the dynamic range

[2] The Waweforms program can be downloaded from Digilents homepage, www.digilent.com

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needed to accurately receive the low signals from the embedded magnetic microwires would be difficult to tackle when used in dynamic environments.

The only viable solution was to use microwires exclusively on the outer surface of the coupons facing the reader. Several 55x300mm coupons with magnetic microwires of the optimised CoFeSiB-alloy on one of the surfaces were fabricated and used as a project standard sensorised coupons. The coupons were distributed to all partners to use when setting up their measurement systems.

In Figure 18 a tension test of a standard sensorised coupon is shown. The transmitting and receiving dual polarized antenna is placed within the zone where the Helmholtz coils produce a homogeneous magnetic field. A few centimetres above it the sensorised coupon is placed with the magnetic microwires in the same direction as the magnetic field and facing the antenna. Signals from the coupon when untensioned and tensioned is shown to the right. The effect of tensioning the microwires is clearly visible by the broadening of the received signal peaks when the applied magnetic field (yellow trace) passes zero.

It is clear that the third version of the portable reader is capable of detecting signals from sensorised coupons with magnetic microwires of the optimised CoFeSiB-alloy that was developed in T2.2. It has also been demonstrated that detecting tensioning of the magnetic microwires can be done with the same equipment.

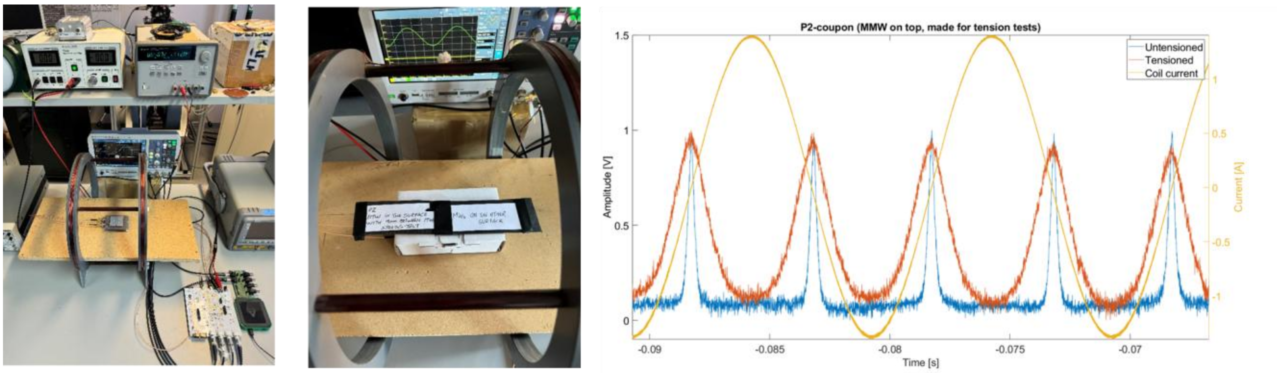

Figure 18 Tension test of a standard sensorised coupon using the third version of the portable reader. In the figure to the right the broadening of the received peaks when the coupon is tensioned are clearly visible.

5.7 DELIVERY OF THE 2.45GHZ PORTABLE READER TO PARTNERS AND E-TRAINING

During spring 2024 delivery of the third version of the 2.45GHz portable reader to project partners started. Each partner was in addition to the supplied assembly instructions offered guidance to set up their systems over Teams-meeting. Since all partners have different conditions in their respective labs as well as different applications the training needed to be tailored to each partner. All partners successfully assembled their systems and were able to conduct measurements using the standard sensorised coupon.

During the general meeting in Cork a demonstration of the high frequency portable reader was performed.

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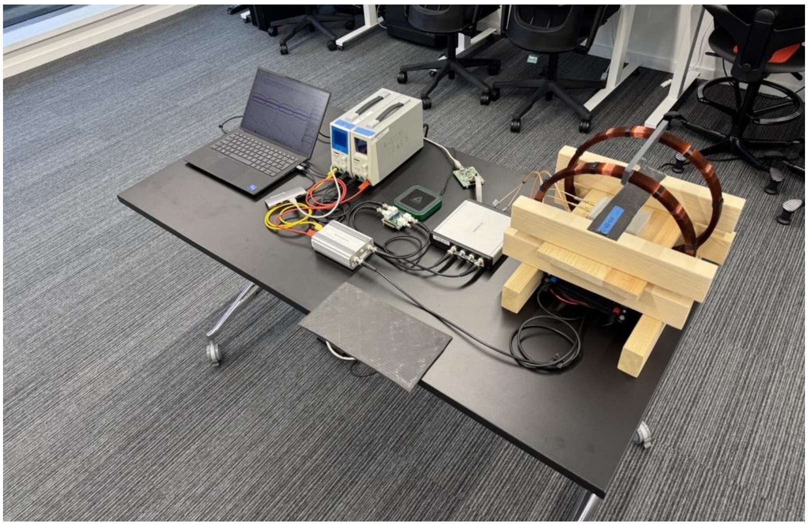

Figure 19 The 2.45GHz portable reader system as demonstrated in the general meeting at Collins Aerospace in Cork.

6. LOW FREQUENCY PORTABLE READER

The problems and limitations associated with the high frequency reader in combination with embedded microwires in carbon fibre composites led to the search for alternative solutions. Also, from an industrial perspective, the use of magnetic microwires could not be restricted only to the surface of carbon fibre structures. A clue for a possible way forward is in Figure 20. The picture shows the results from transmission measurements through several 3mm thick carbon fibre coupons. As can be seen the transmission coefficient S21 increases at lower frequencies. This indicates that if the carrier frequency is lowered from the current 2.45GHz band to below 1GHz or even lower the signal strength will increase as much as 30-40dB. For reflection measurements, as are performed with the high frequency portable reader, that would mean an increase in signal strength of 60-80dB (1000-10000 times) if the magnetic microwires are buried 3mm in below the surface of a carbon fibre structure. Clearly this would decrease the attenuation due to carbon fibre content to virtually zero at very low frequencies.

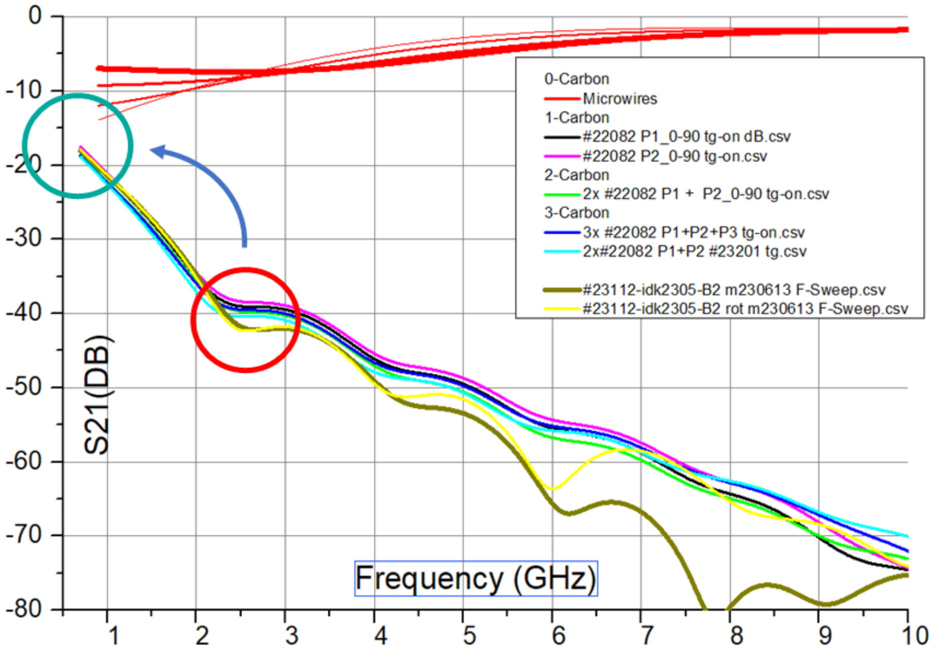

Figure 20 Transmission measurement of a 3mm thick carbon fibre coupon. The change of carrier frequency from 2.45GHz ISM band to below 1GHz would increase the signal strength of about 20dB. If extrapolating even further, carrier frequencies below 100MHz would increase the signal strength up between 30 to 40dB.

The ideas that lowering the carrier frequency would be beneficial is supported by the simulation work performed by CAE and reported in D2.4. The simulation shows that the attenuation due to carbon fibre content decreases to close to zero below 50MHz. Also reported in D2.4, the first trials using lower frequencies at 433MHz to probe microwires in a project-standard coupon with substantially higher signal to noise ratio than at 2.45GHz.

6.1 FIRST LOW FREQUENCY PORTABLE READER VERSION

Using frequencies as low as 50MHz or lower would make the antennas prohibitively large (3m and larger). Therefore magnetic coils were proposed instead. Although, they would not make it possible to perform free space measurements or using the giant magneto impedance of the microwires, it would be possible to make near field non-contact measurements of the state of the magnetic microwires embedded in carbon fibre structures.
The first attempts used a differential coupled 100mm coil system, originally developed for measuring properties of magnetic ribbons, together with a vector network analyser at 1MHz carrier frequency. All coupons tested gave high signal to noise ratio.

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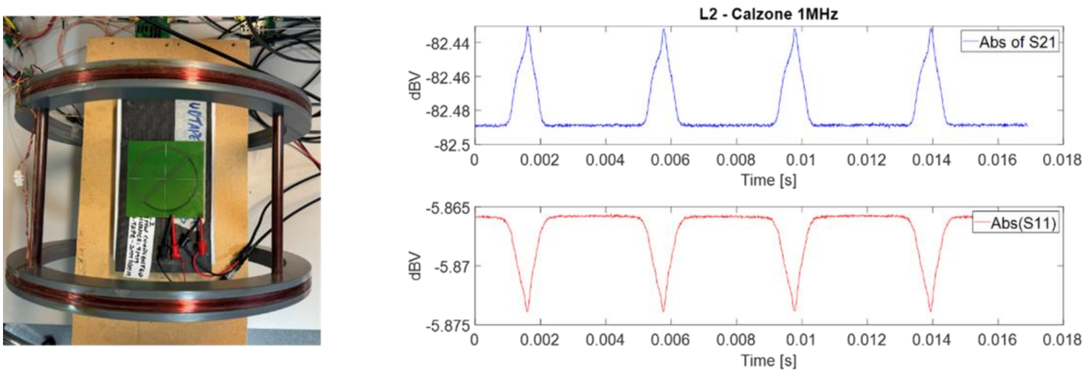

Figure 21 Left: The differential coil system (green square) used for the 1MHz tests. Right: The measurements of the reflection and transmission coefficients show clear peaks originating from the response of the embedded magnetic microwires 3mm below surface in a carbon composite coupon.

To decrease the size a similar set-up using standard RFID-coils for 13.56MHz was constructed. Two coils in series next to each other on top of a carbon fibre coupon would produce a horizontal magnetic field to probe the magnetic microwires embedded. in the coupon. Then a similar pair of coils was placed below the first pair as a receiving coil pair as shown in Figure 22.

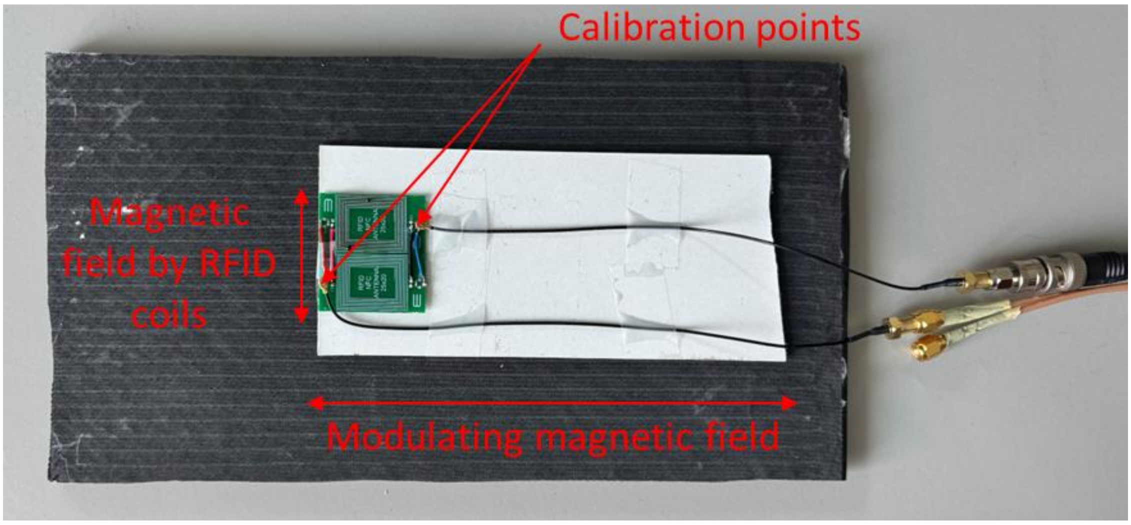

Figure 22 First prototype using RFID-coils on top of a carbon fibre coupon.

For excitation the Helmholtz coils were used. 65 measurements, one each 5mm, along the centre line (left to right of the coupon in the picture) of the coupon were made. The results from measurements number 15 using a VNA at 2MHz is shown in Figure 23. All four scattering parameters show clear peaks originating from the magnetic microwires embedded in the carbon fibre composite.

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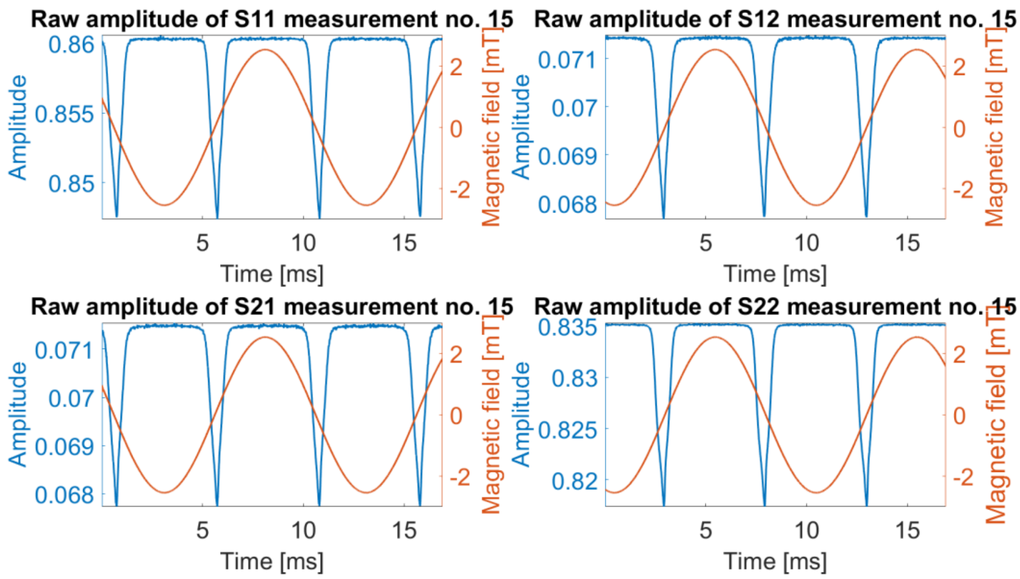

Figure 23 Measurement of the scattering parameters from embedded magnetic microwires in a carbon fibre coupon using a VNA at 2MHz.

Combining all the measurements from the line scan in four normalised amplitude pictures, one for each scattering parameter, as in Figure 24, it can be seen that there exist edge effects close to the edges of the coupon, i.e. widening of the blue coloured dips at for example time stamp 540.

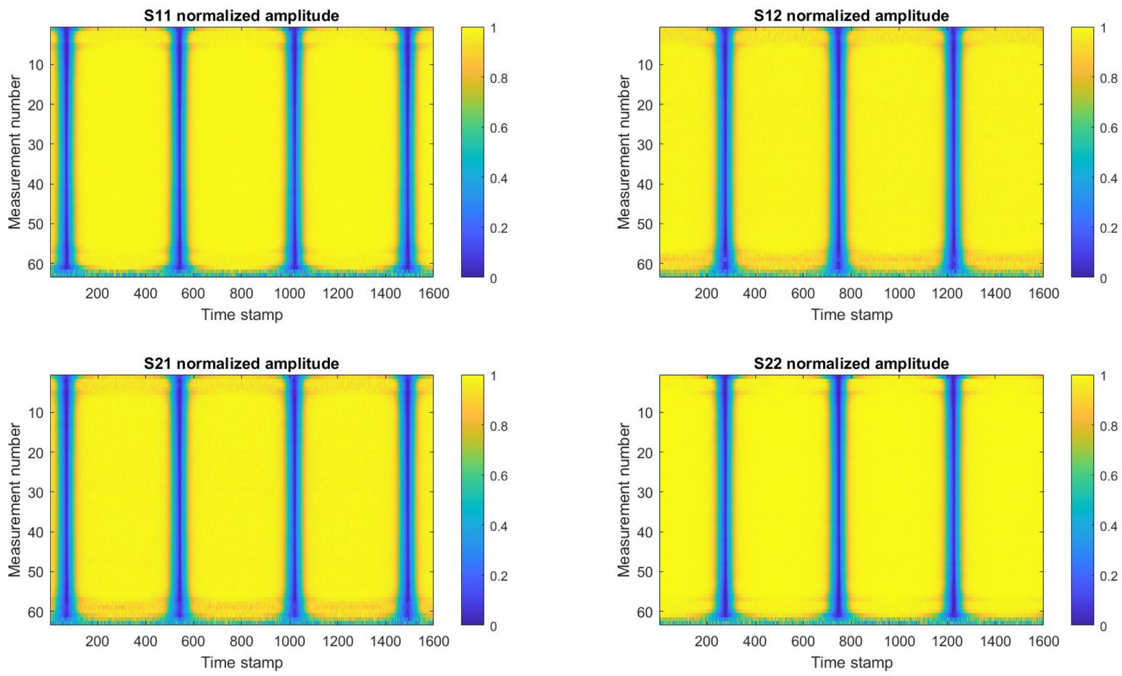

Figure 24 Amplitudes from all four scattering parameters along the measured line.

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A close-up of the amplitude of the reflection coefficient S11 in Figure 24 is shown in Figure 25. There exists a widening of the dip at time stamp 540 in the edges, but also at some distance from the edge at for example measurements between 12 and 20 which is equivalent to 6-10cm from the edge. This indicates that there exist internal differences in stress that are not related to edge effects.

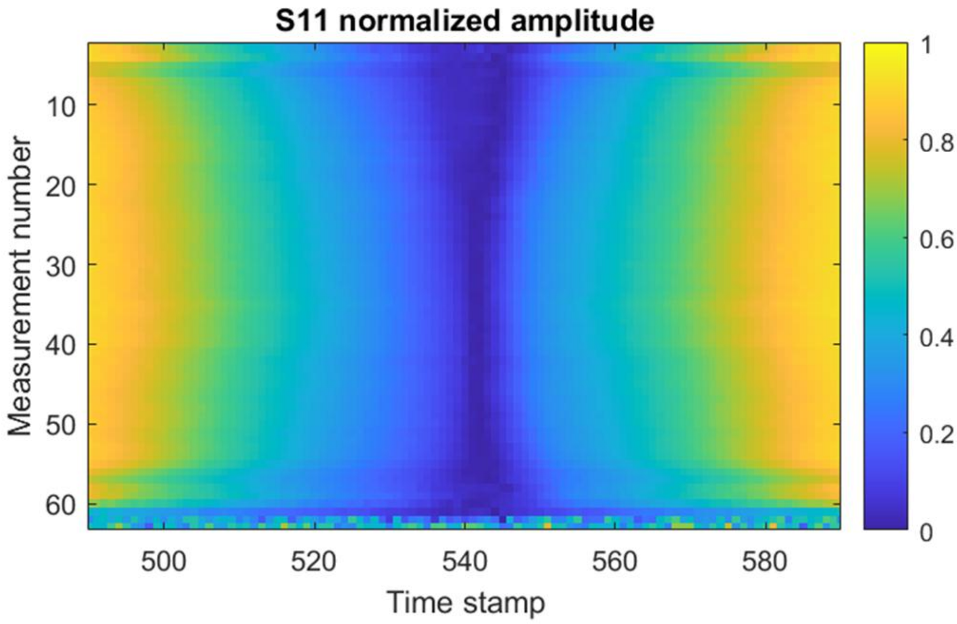


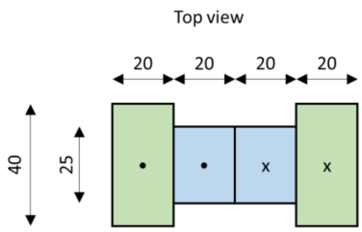
Figure 25 Close-up of Figure 23 around time stampp 540.

From the results of the measurements, it can be concluded that the measurement technique may be used for structural health monitoring.

6.2 LOW FREQUENCY READER USING CUSTOM PCBS

To further develop the low frequency reader towards a tool for structural health monitoring a PCB with the same structure as the previous one described in section 6.1, i.e. one planar coil pair in series for transmitting the carrier frequency and one coil pair in series below used for reception. Also, the bulky Helmholtz coils need to be incorporated on the same PCB, making the whole reader a planar structure more suitable for a practical portable reader.

In Figure 26 a top view sketch of the PCB is shown. The centre coils(blue) mentioned in the previous section have the coils responsible for the modulating field (green) placed to the left and right, replacing the Helmholtz coils.



- Modulating field coils traces width: 0.3mm
- Number of turns: 12
- Rx and Tx coils traces width: 0.15mm

Figure 26 Top view sketch of the first planar low frequency reader.

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To increase the efficiency of the reader a multi-layer structure was chosen. The modulating coils consists of eight layers and the transmitting and receiving coils consists of four layer each. A side view of the stack up of the PCB is shown in Figure 27.

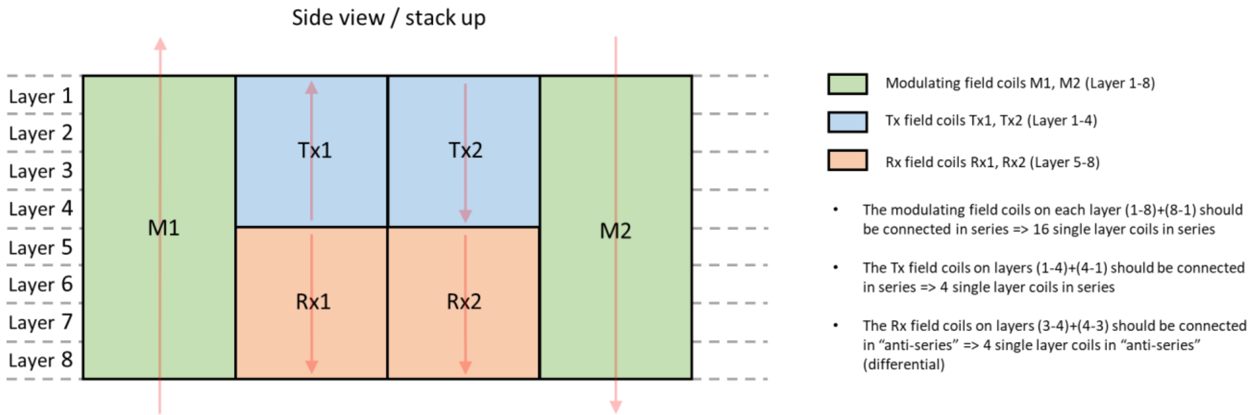

Figure 27 Stack up of the first custom PCB for the planar low frequency reader. The magnetic fields produced are indicated by light red arrows.

The fabricated PCB, see Figure 28, includes four SMA-connectors to connect to the adaptor card used for the high frequency portable reader. The modulating coils are labelled L1 and L4. The transmitting coils are labelled L2 and L3. The receiving coils are located directly below the L2 and L3 coils.

Figure 28 The first version of the planar low frequency reader card.

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6.2.1 THE FINAL VERSION OF THE PLANAR LOW FREQUENCY READER

To further make the low frequency reader suitable for field work the next version (v.1.3) incorporates a network cable connector in addition to the four SMA-connectors. This extra connector together with an extra adaptor card will make it easier to move the PCB to different locations using only one cable.

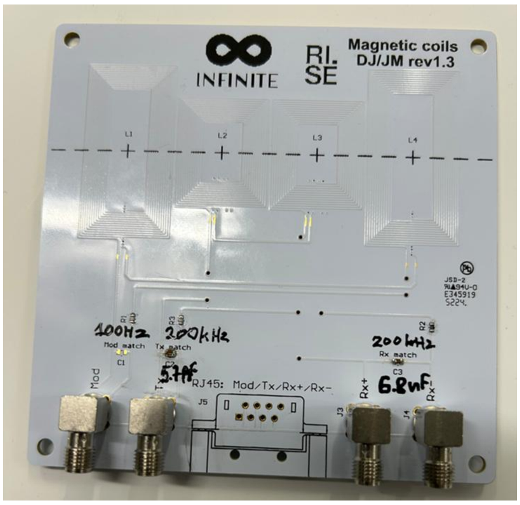

Figure 29 The final version of the planar low frequency portable reader card.

The complete low frequency system consists of an Analog Discovery 3, an adaptor card, the low frequency amplifier and a frontend planar coil card (v.1.3) plus additional cables. This set up is shown in Figure 30. All partners have this set up and have received training on it.

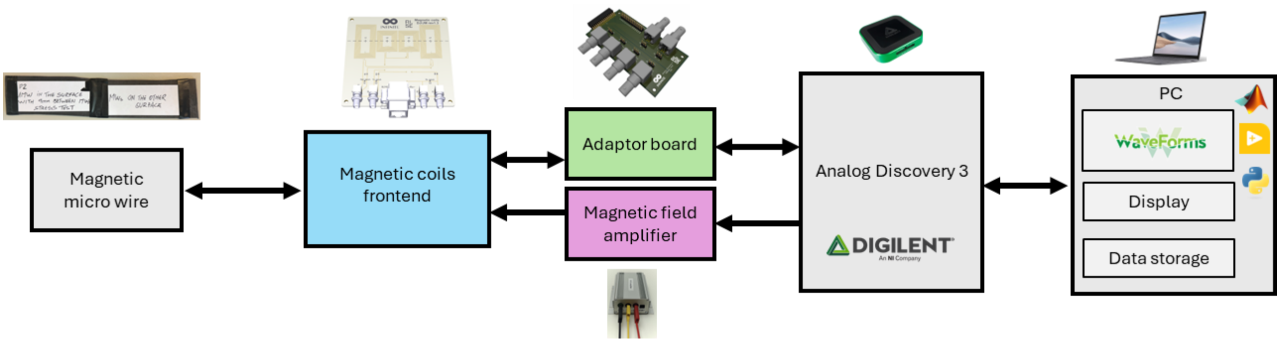

Figure 30 The complete low frequency planar portable reader system.

6.2.2 SIMULATIONS AND VERIFICATION

To better understand the performance of the low frequency front end card magnetic field simulations using COMSOL were performed together with supplementary measurements. The field strength of the magnetic field in the direction of the magnetic microwires generated by the modulating coils and the transmitting coils were studied.

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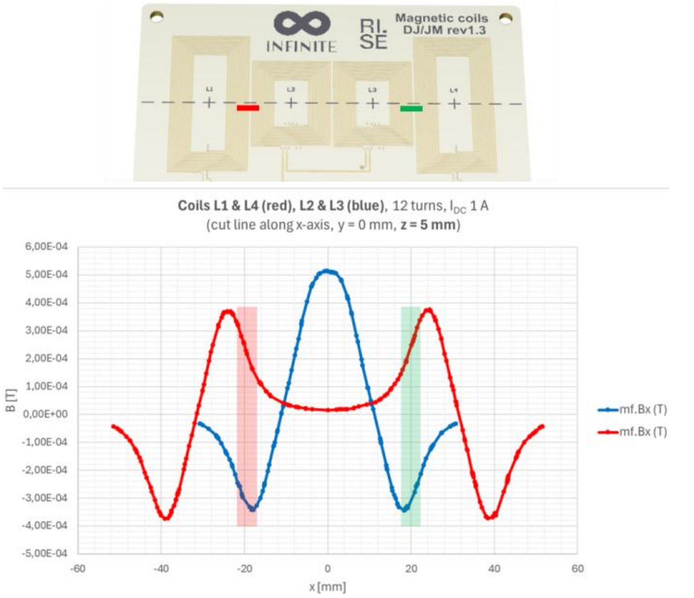

Figure 31 Simulated magnetic fields in the same direction as the dotted line in the upper picture generated by the modulation coils(red) and the transmitting coils(blue). The red and green markings indicates where maximum sensitivity is experienced, however at different polarity.

The simulations of the generated magnetic fields shows that the maximum overlap of the fields generated from the modulation coils and the transmitting coils are located between the modulation coils and the transmitting coils as indicated by the red and green bars in Figure 31. Measurements of the generated field using a Hall-effect sensor shows the same information as indicated in Figure 32.

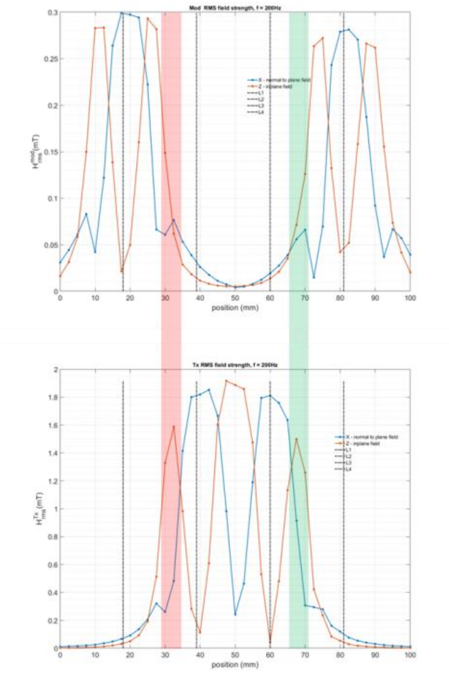

Figure 32 Measured magnetic fields generated by the modulating and transmitting coils. The green and red rectangles indicates where maximum overlap of the fields, and hence maximum sensitivity of the planar coil system are located.

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6.2.3 TUNING OF THE TRANSMITTING AND RECEIVING COILS

To increase the signal strength of the planar low frequency coil system, tuning or impedance matching of the coils were performed. Using a calibrated vector network analyser the impedance of both coil systems were measured. The transmitting coils should have as low impedance as possible at the transmitting frequency, i.e. 200kHz since the generated magnetic field is proportional to the current through it indicating that a series capacitance should be inserted. The receiving coil system should have as high impedance as possible since both ends of the coil system are connected the Analog Discovery's high impedance inputs of 1MOhm indicating that a parallel capacitance should be used as indicated in Figure 33.

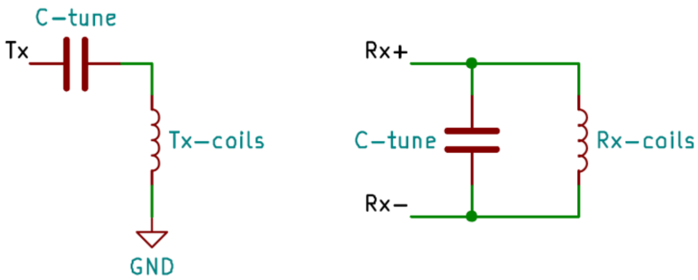

Figure 33 Placement of the tuning capacitances for the planar low frequency portable reader.

Using the formula for a LC-resonance circuit

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

and the measured inductances, the tuning capacitances can be calculated. They were found to be 5.6nF and 6.8nF. In Figure 34 the effect of the tuning for the receiving coils is shown.

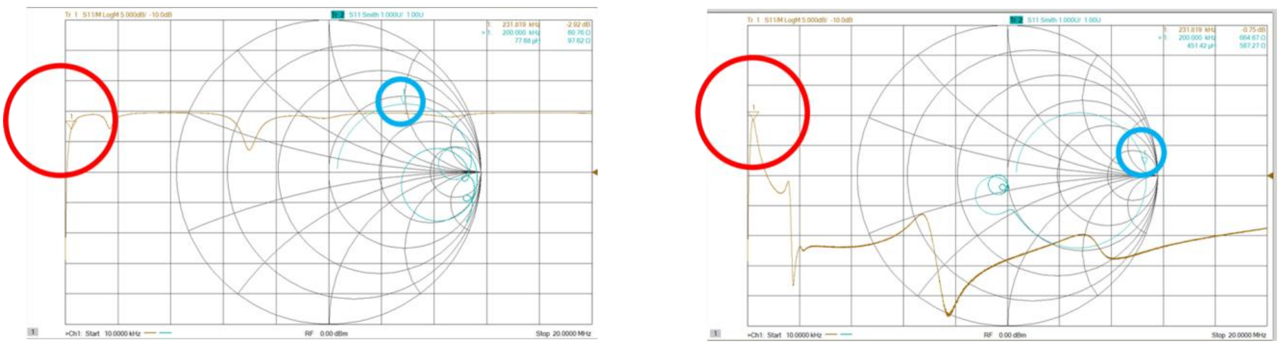

Figure 34 Frequency response and Smith-chart before and after tuning of the receiving coils. Note in the Smith chart that the impedance increases and at the same time the total impedance (blue circles) is almost real when tuned (right picture). Also note that there is a distinct peak at 200kHz in the frequency response (red circles) when the coils are tuned.

The total effect due to the tuning of the coil systems is shown in Figure 35. Almost a tenfold increase in signal strength was observed.

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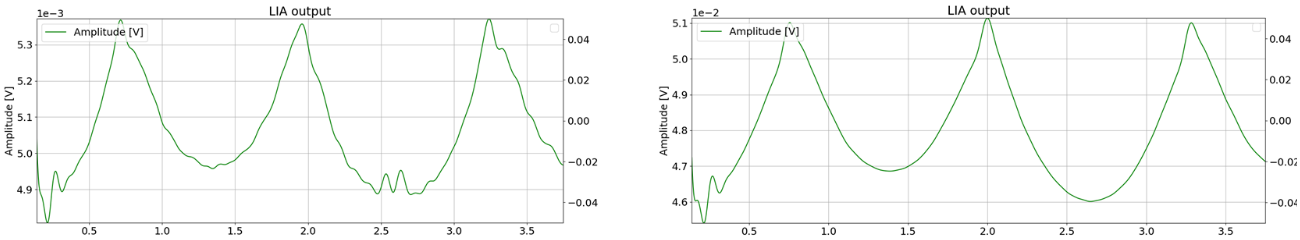

Figure 35 The effect of tuning the transmitting and receiving coils is an increase of received signal strength of almost ten times as indicated in the right picture compared to the left.

6.2.4 MEASUREMENTS

A test to observe the performance of the planar low frequency reader was performed. A project standard sensorised coupon was placed In a MARK10 force/strain tester. A force of up to 300N was applied and the response of the magnetic microwires were recorded.

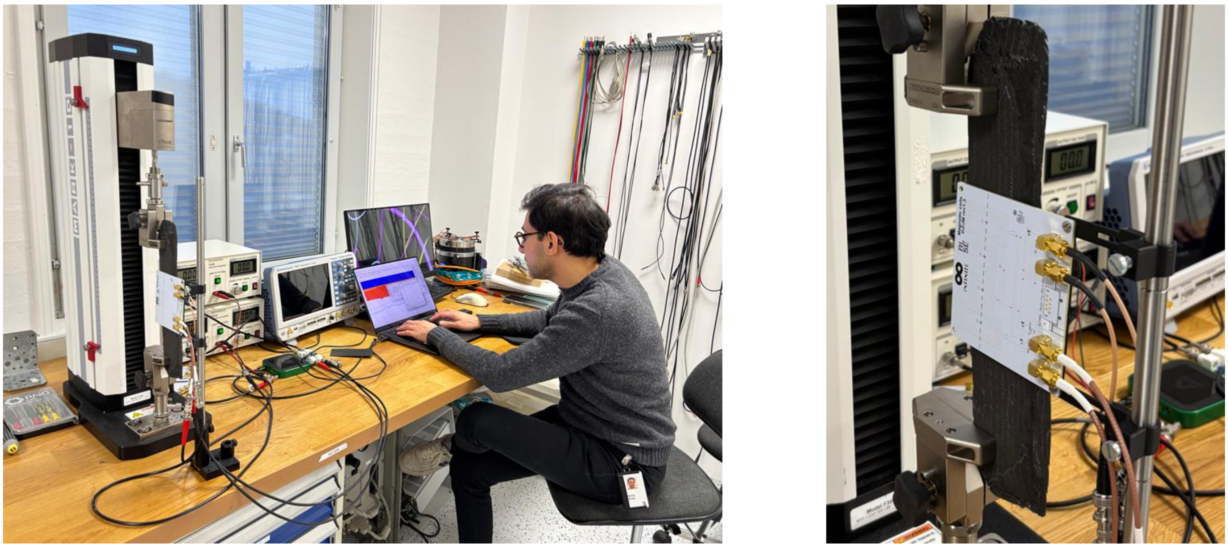

Figure 36 The test set-up for testing the performance of the planar low-frequency portable reader.

The results from the measurements in shown in Figure 37 show a high signal to noise ratio and a correlation between the applied load and the width of the received peaks. The results are consistent with theory.

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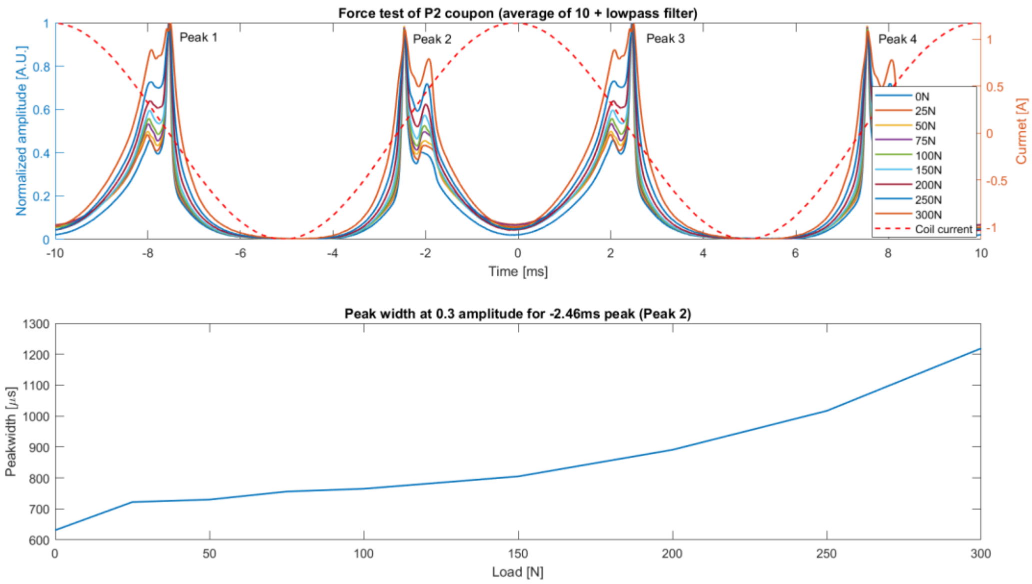

Figure 37 The result of applying a force of up to 300N to a project standard sensorised coupon is shown.

6.3 SOFTWARE

To facilitate usage and measurements using the planar low frequency portable reader a graphical user interface was developed in Python. Some parameters such as both carrier and modulation frequency and amplitude as well as low pass filter bandwidth can be set by the user. However, the default settings should be sufficient for most normal measurement situations. The signal processing such as down conversion of the carrier that in the high frequency version of the portable reader is done in hardware is done in software for the low frequency version. The memory size of the Analog Discovery limits the carrier frequency to be about 200kHz. Received data can be stored on disk. One csv-file for each conducted measurement. A measurement file consists of a header holding information about current measurement settings. Thereafter approximate 15200 rows of data in six columns is stored. The data stored are a time-vector, raw data for the two input channels, in-phase and quadrature data from the digital lock-in amplifier and amplitude of the modulating magnetic field.

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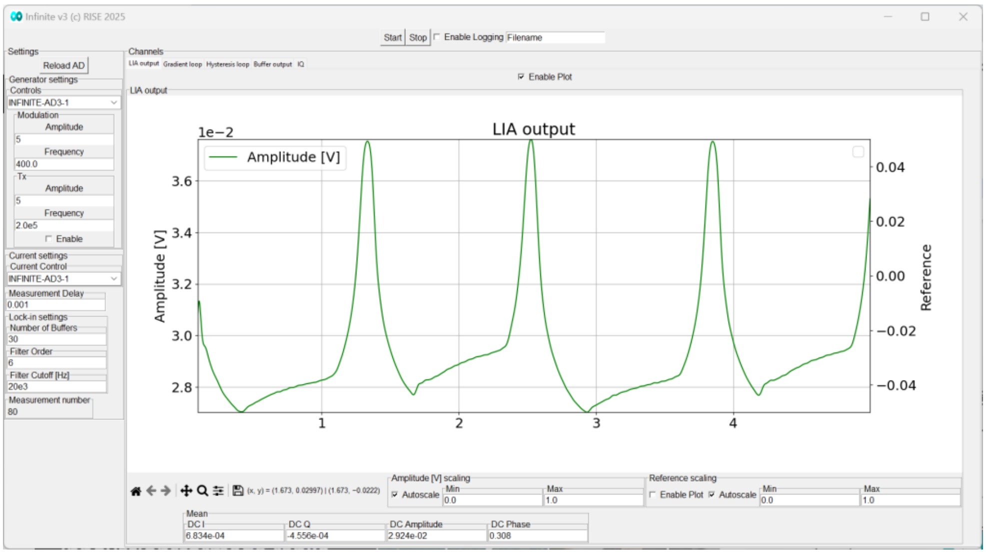

Figure 38 The graphical user interface developed for the low frequency portable reader during measurement of a sensorised magnetic microwire.

6.4 OUTLOOK

One of the objectives of the INFINITE-project is to find a method to use magnetic microwires embedded in carbon fibre composite structures for structural health monitoring. To test the design of the planar low frequency portable reader, a prototype consisting of a custom-made PCB consisting of the same coil system as described in section 6.2 but with a different form factor to fit a 3D-printed holder. The prototype is connected to the Analog Discovery 3 via an adaptor card and a network cable making it possible to scan a carbon fibre structure and hence structural health monitoring would be possible

Figure 39 3D-printed prototype for canning magnetic microwire sensorised carbon fibre structures.

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7. CONCLUSIONS

- Increase of signal strength of the new magnetic microwire composition is verified in coupons at 2.45GHz
- A 2.45GHz portable reader system has been delivered to the partners
- A successful demonstration of the 2.45GHz portable reader system was carried out during the GM30 in Cork
- Low frequency readers have been delivered to five partners. Education in operation of the equipment has been caried out.
- A graphical user interface that can present and save raw as well as processed data from the low frequency portable reader has been developed.
- A prototype of a low frequency handheld reader that can be used for basic structural health monitoring of carbon fibre composites containing magnetic microwires have been developed.

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8. APPENDIX A – 2.45GHZ TRANSCEIVER SCHEMATICS AND LAYOUT

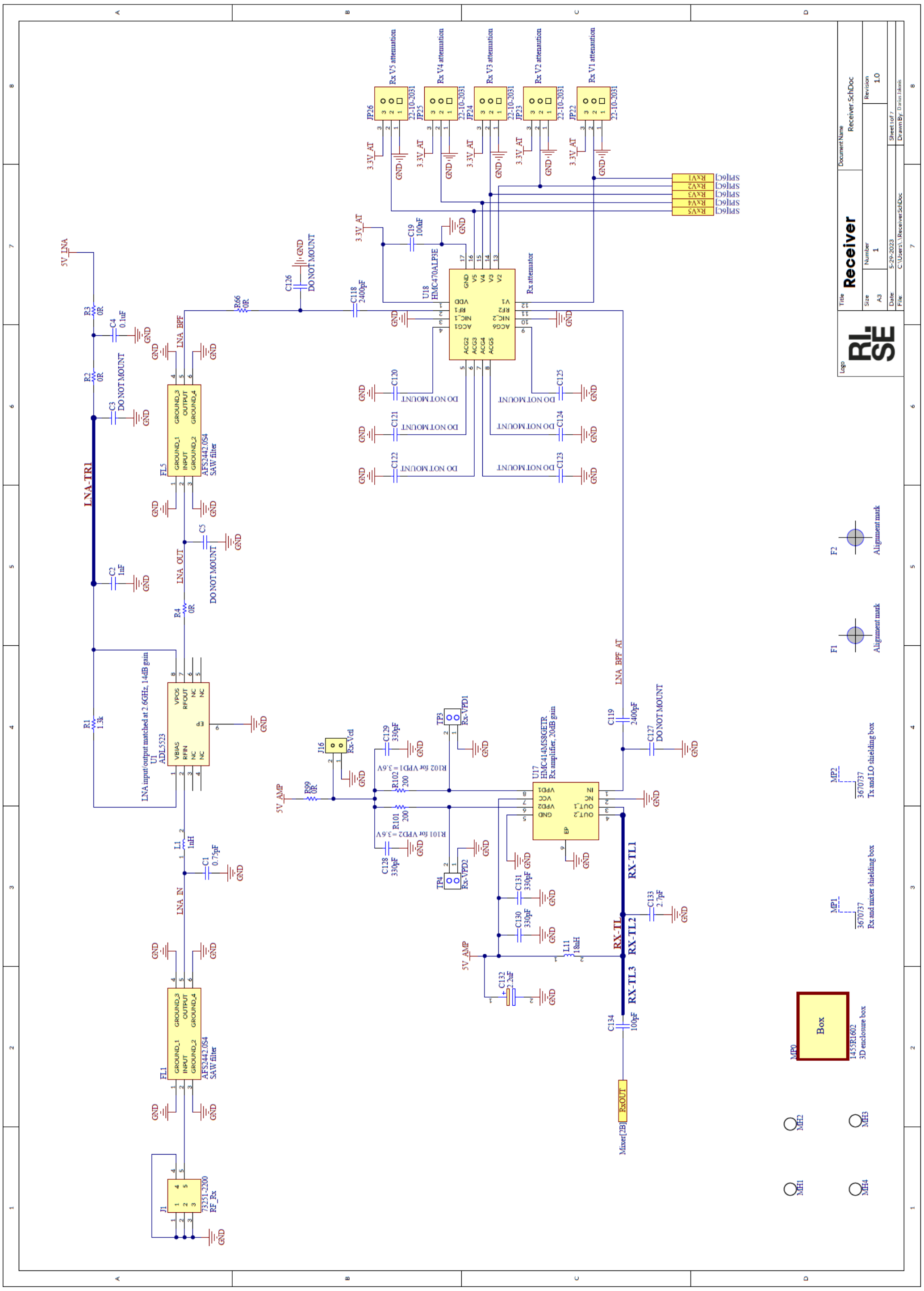

Figure 40 Schematics of the receiver section

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

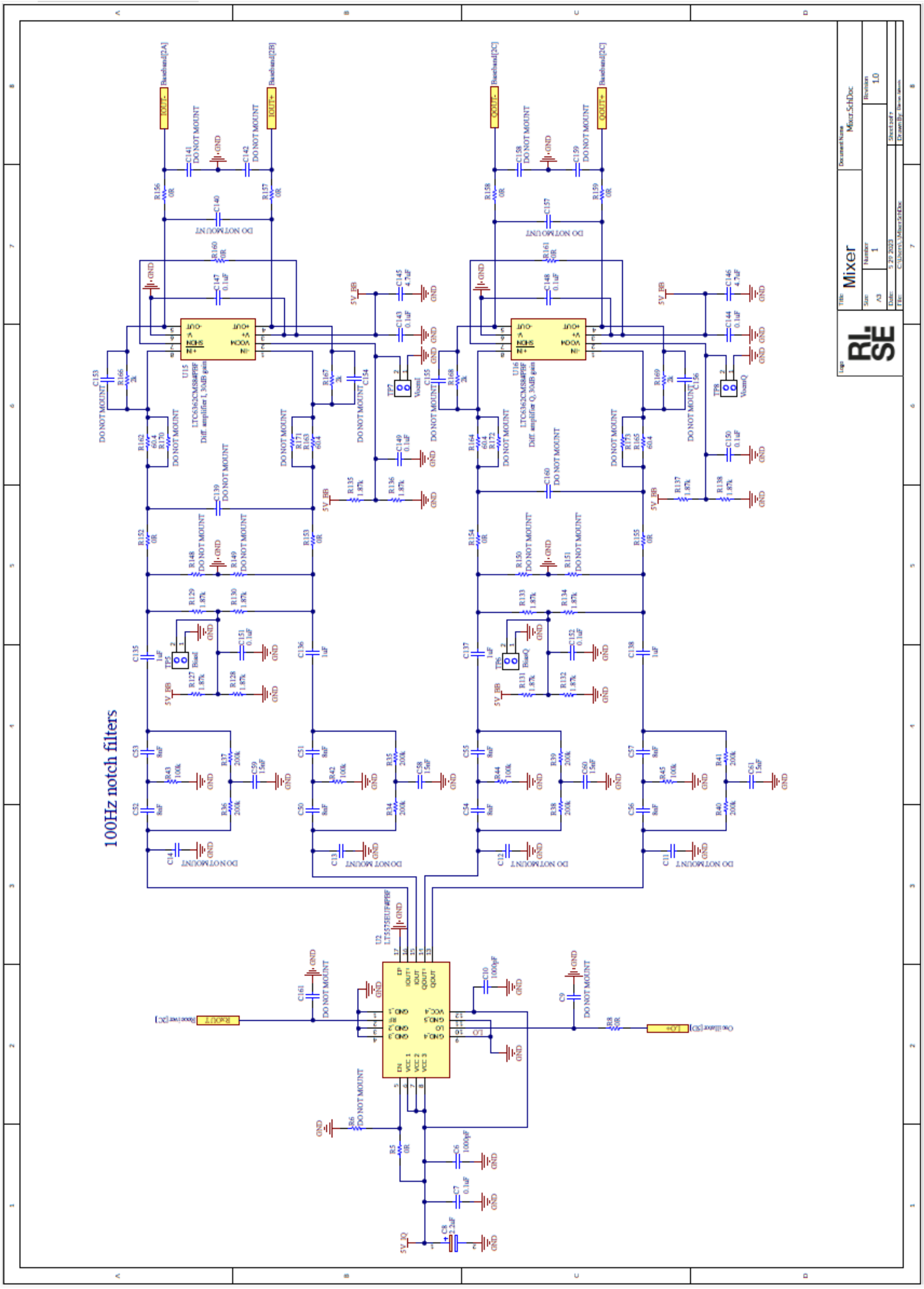

Figure 41 Schematics of the mixer section.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

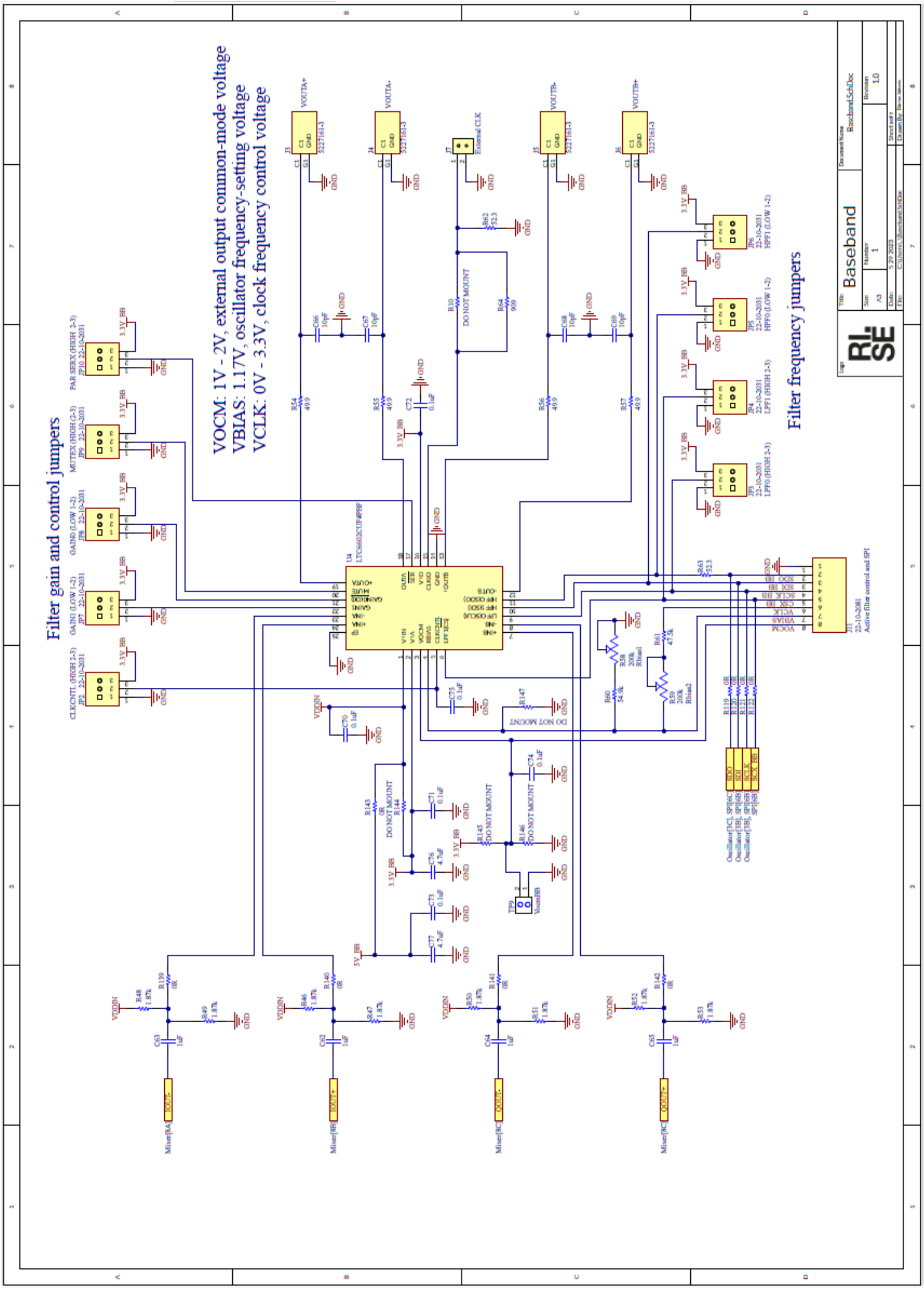

Figure 42 Schematics of the baseband section.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

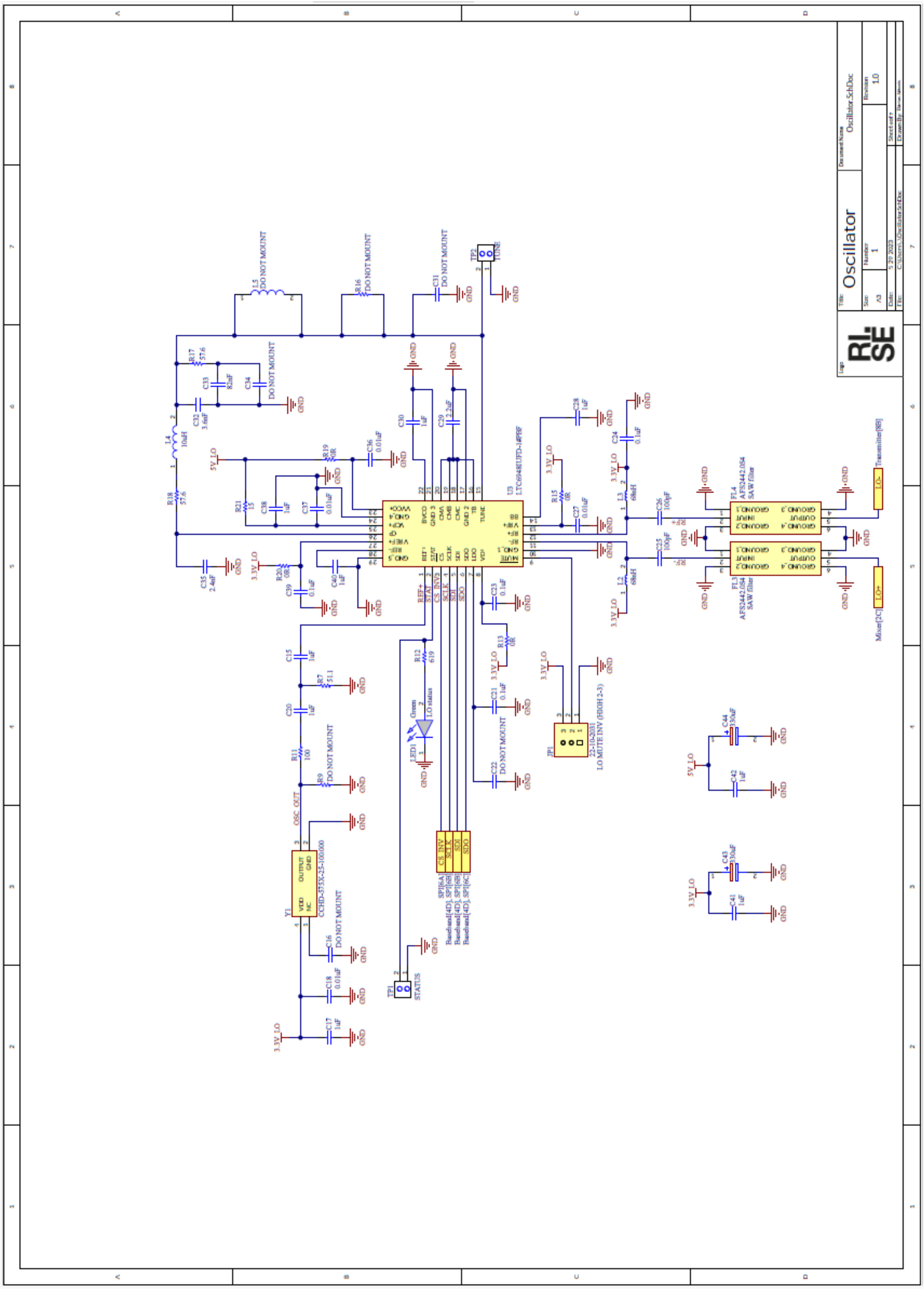

Figure 43 Schematics of the oscillator section

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

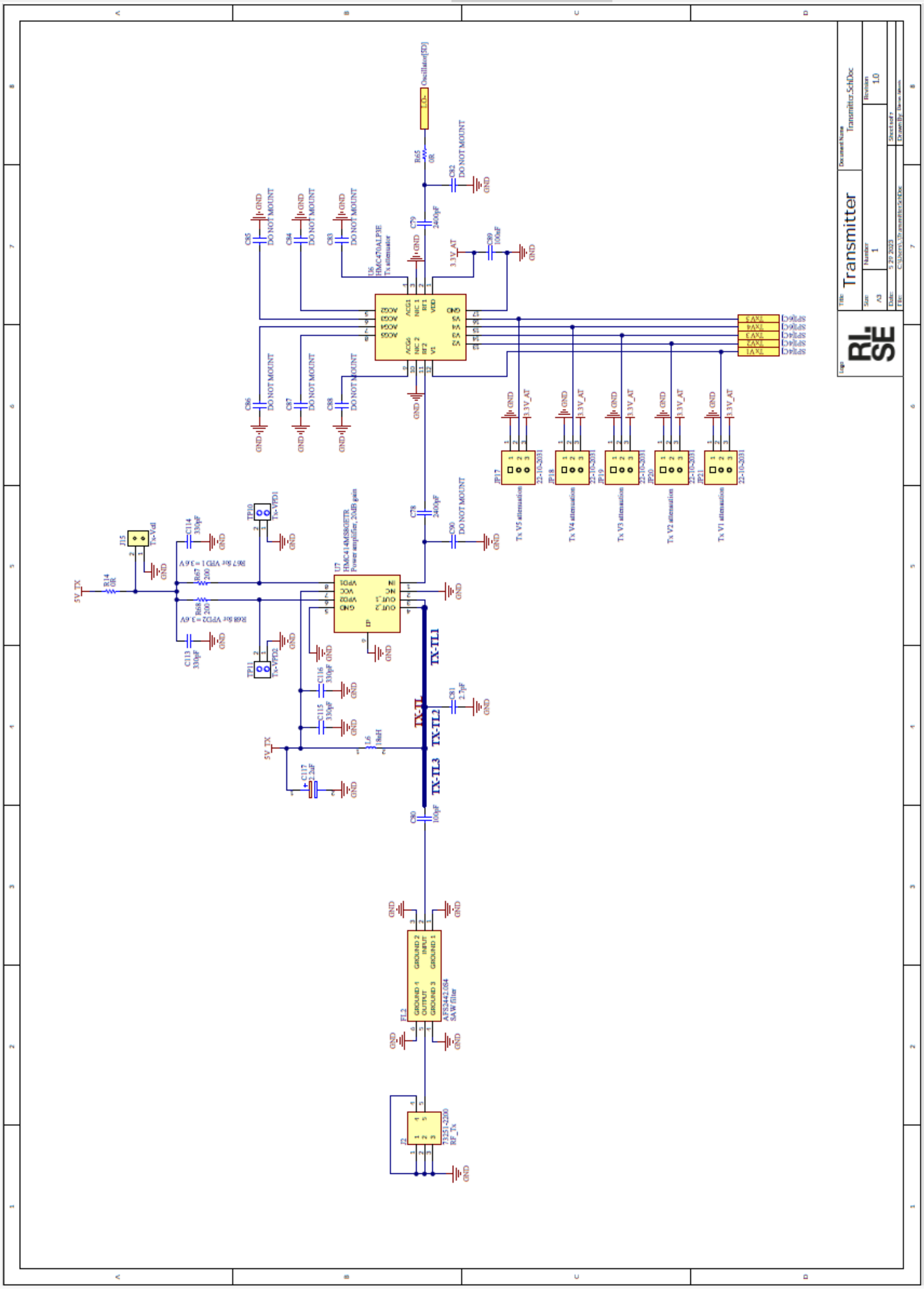

Figure 44 Schematics of the transmitter section.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

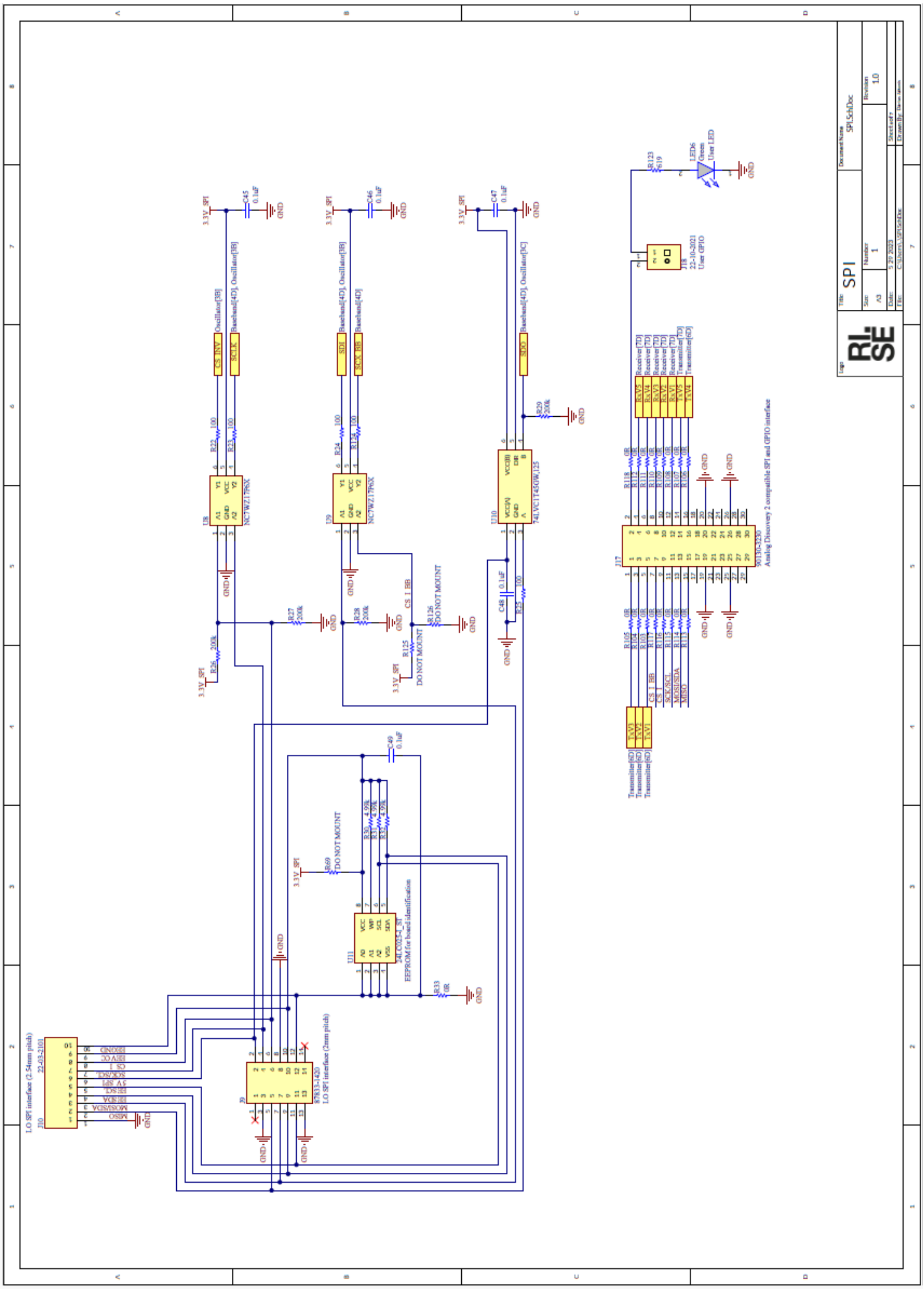

Figure 45 Schematics of the SPI-programming section.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

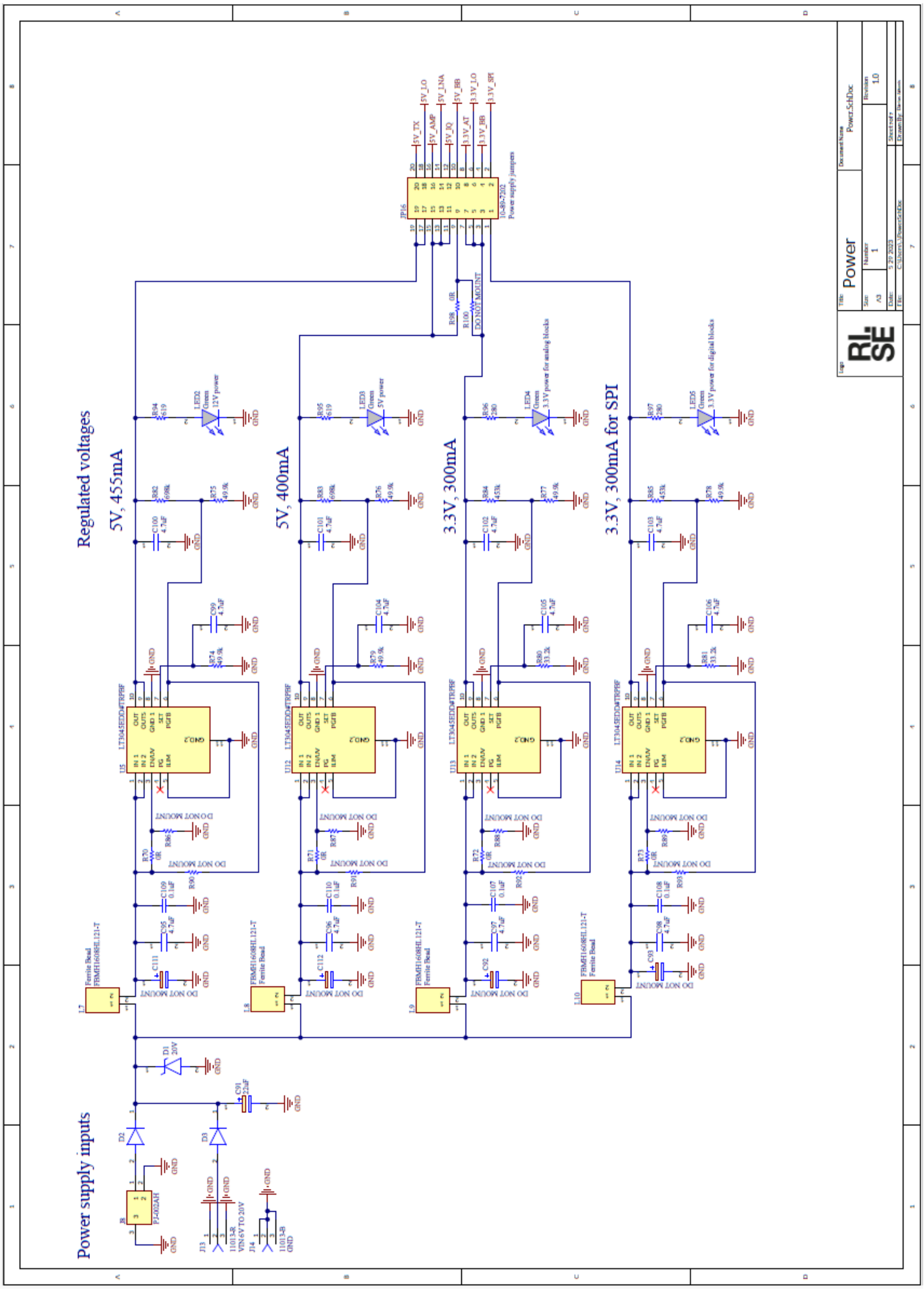

Figure 46 Schematics of the power section.

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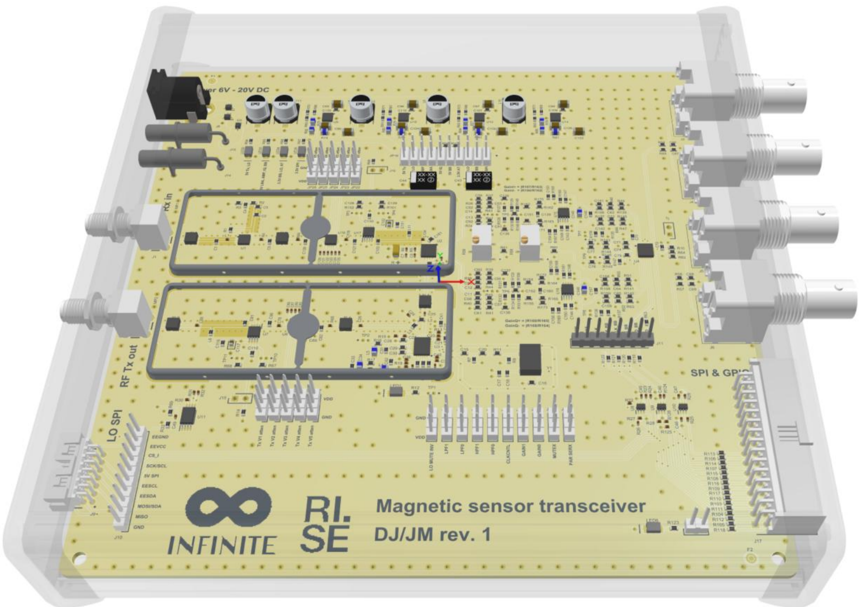

Figure 47 3D picture of the transceiver PCB mounted in a shielding box.

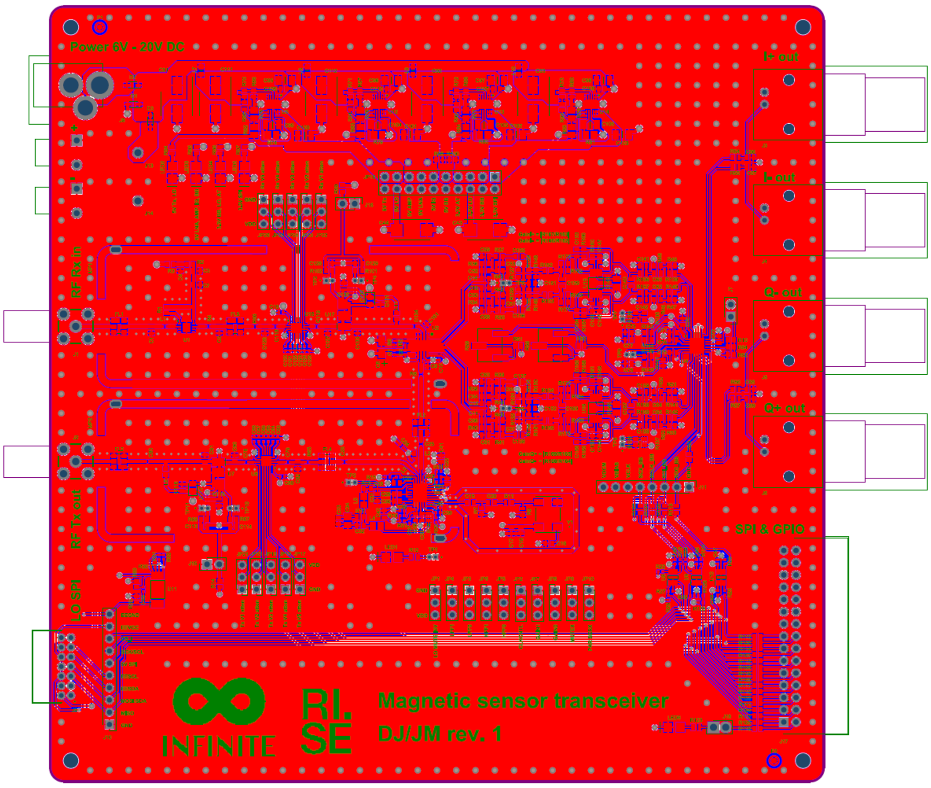

Figure 48 Overview of the 2.45GHz transceiver.

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9. APPENDIX B – LOW FREQUENCY AMPLIFIER SCHEMATICS AND LAYOUT

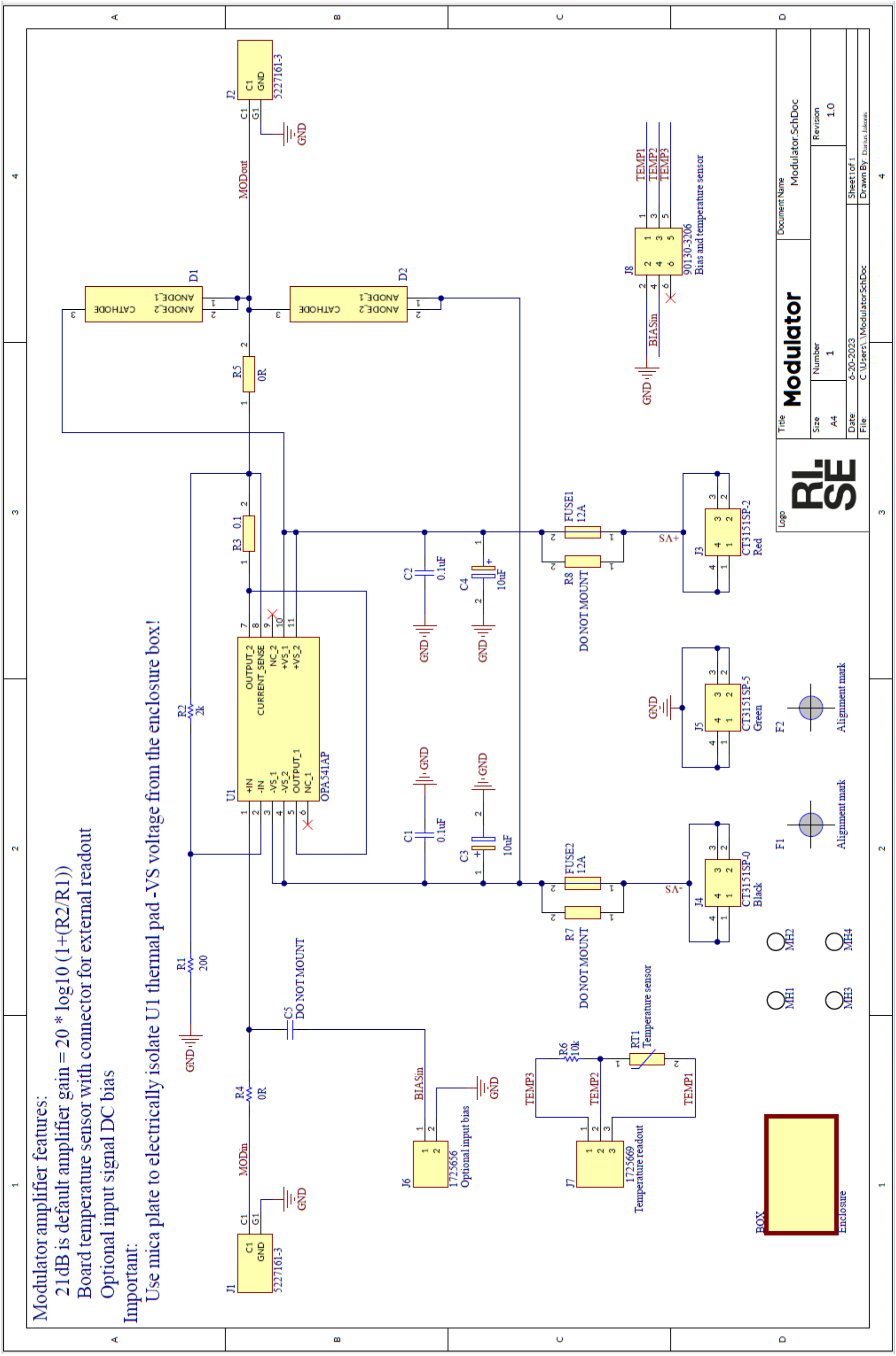

Figure 49 Schematics of the low frequency amplifier

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

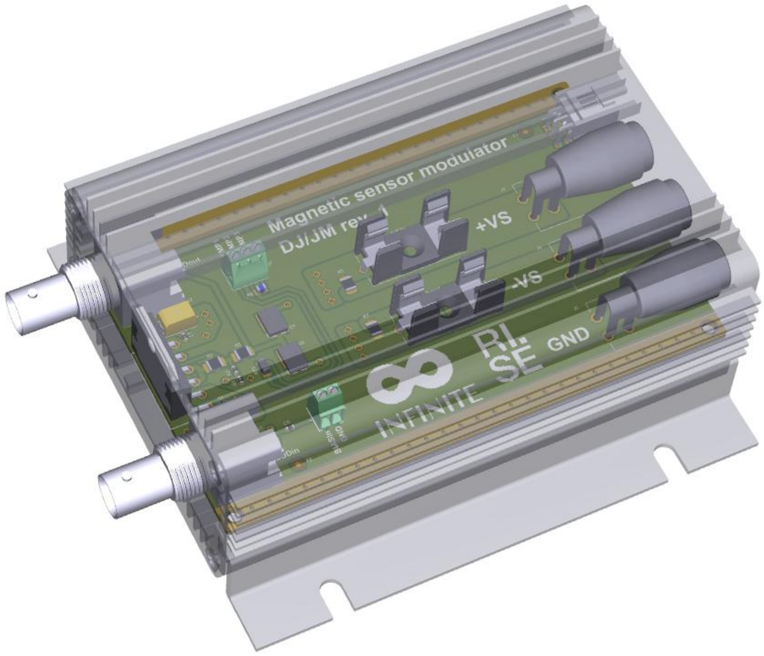

Figure 50 3D picture of the low frequency amplifier mounted in a shielding box

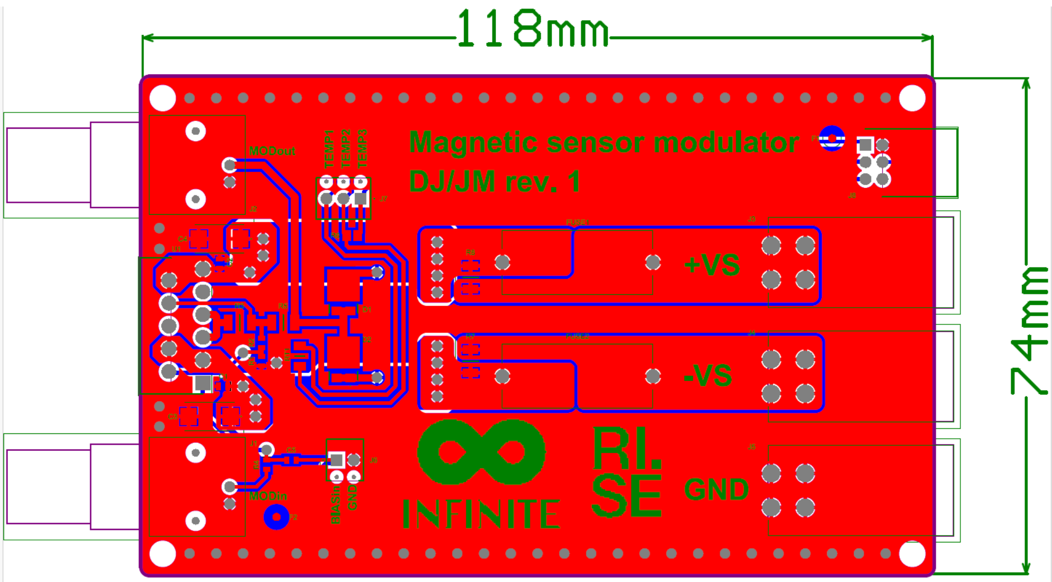

Figure 51 Overview of the low frequency amplifier PCB

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10. APPENDIX C - ADAPTER CARD SCHEMATICS AND LAYOUT

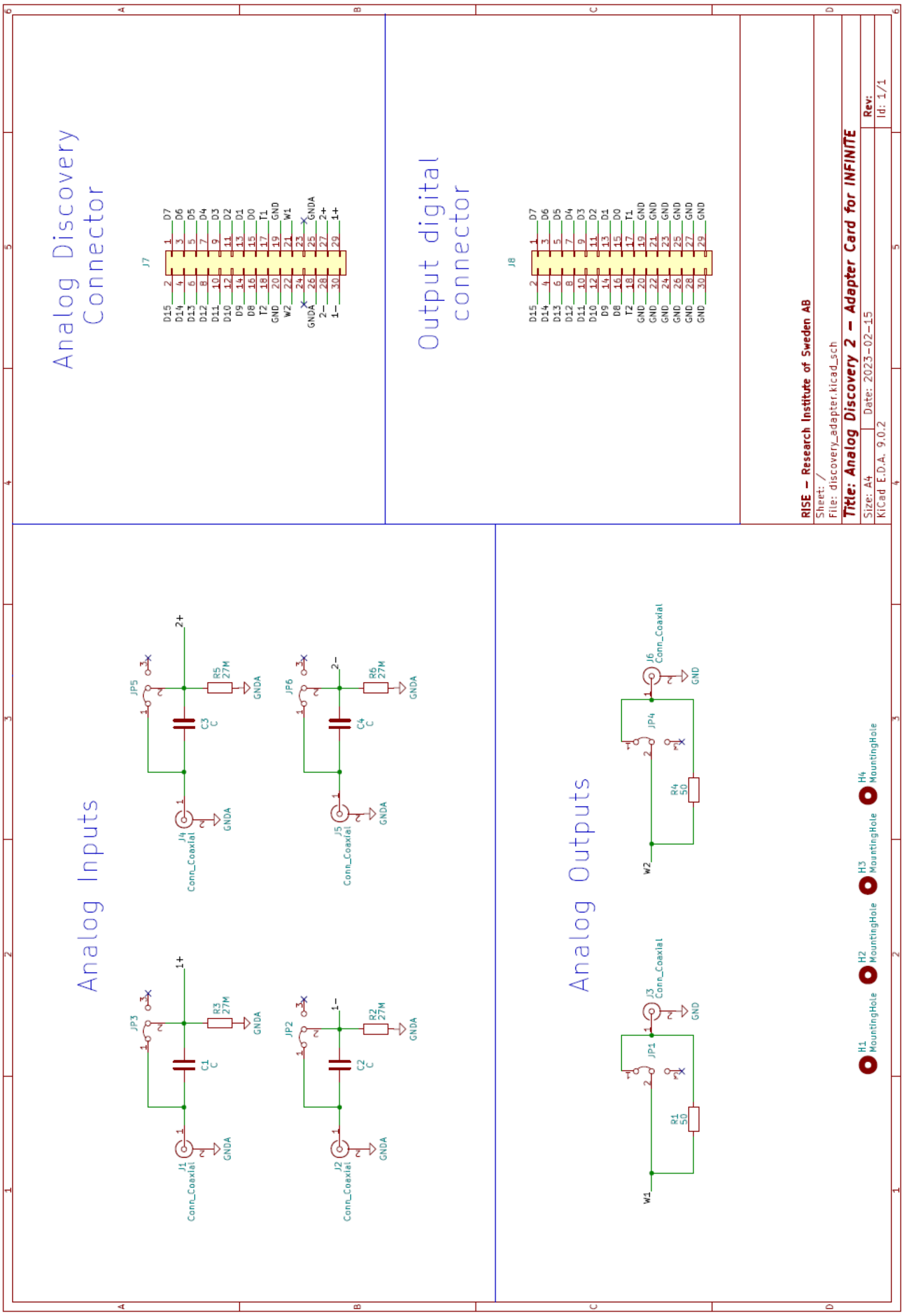

Figure 52 Schematics of the adaptor card for the high frequency portable reader.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

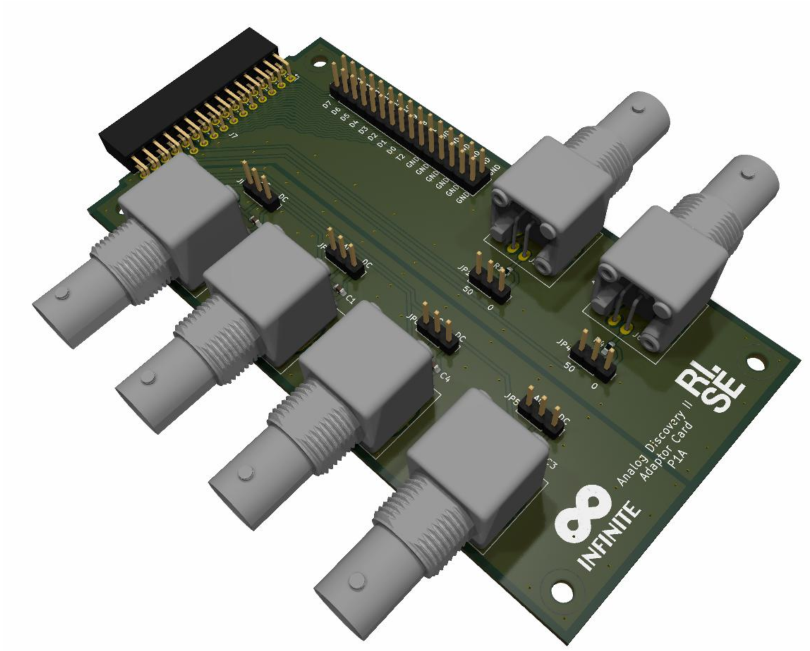

Figure 53 3D picture of the adaptor card for the high frequency portable reader.

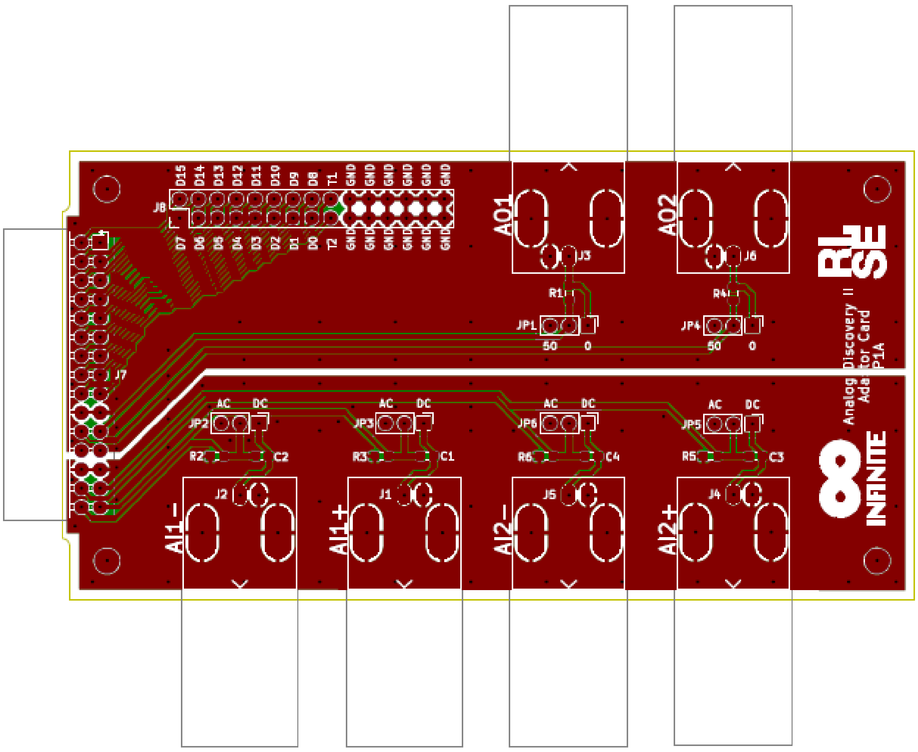

Figure 54 Overview of the adaptor card for the high frequency portable reader.

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11. APPENDIX D – FIRST VERSION OF THE PLANAR LOW FREQUENCY READER

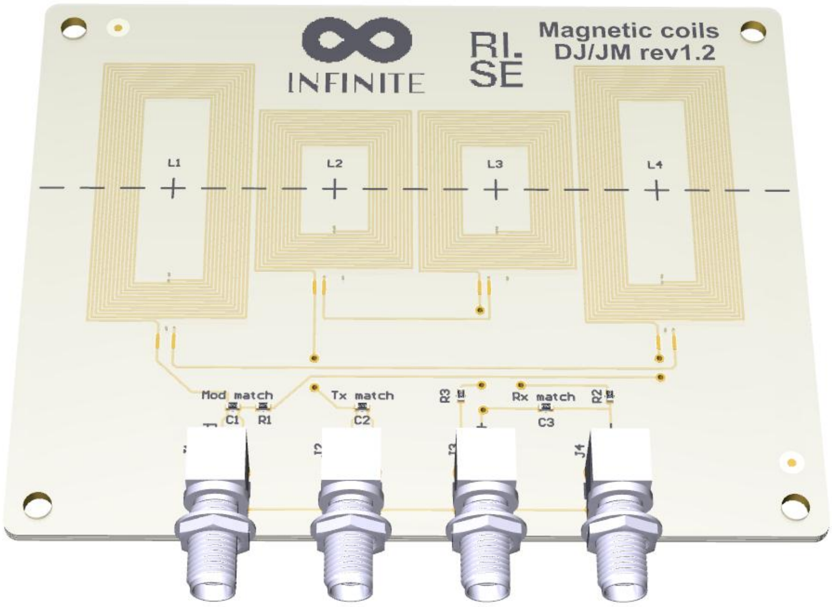

Figure 55 3D picutre of the first version of the planar low frequency reader.

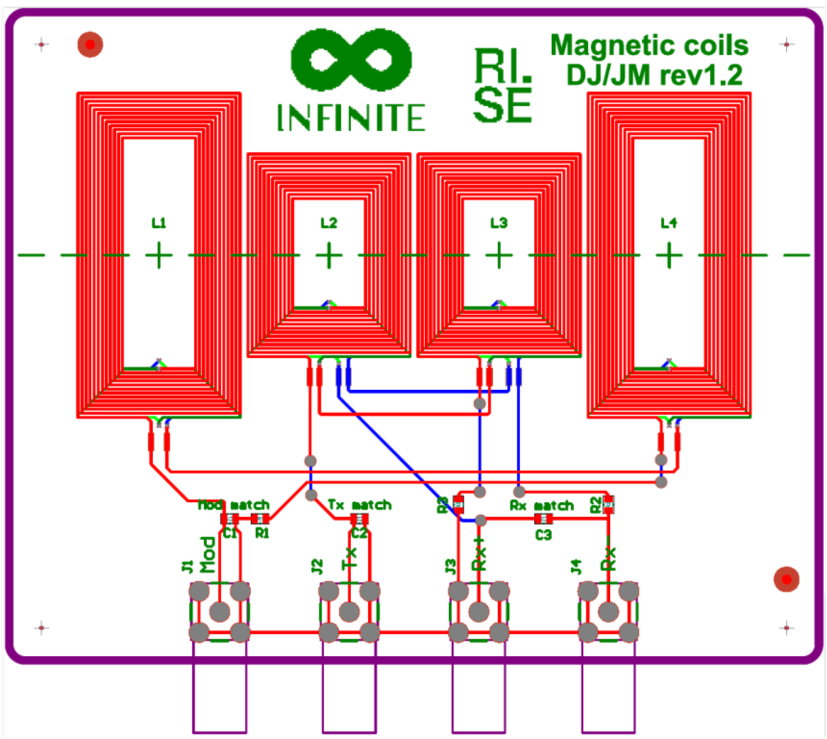

Figure 56 Overview of the first version of the planar low frequency reader.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

12. APPENDIX E – VERSION 1.3 OF THE PLANAR LOW FREQUENCY READER

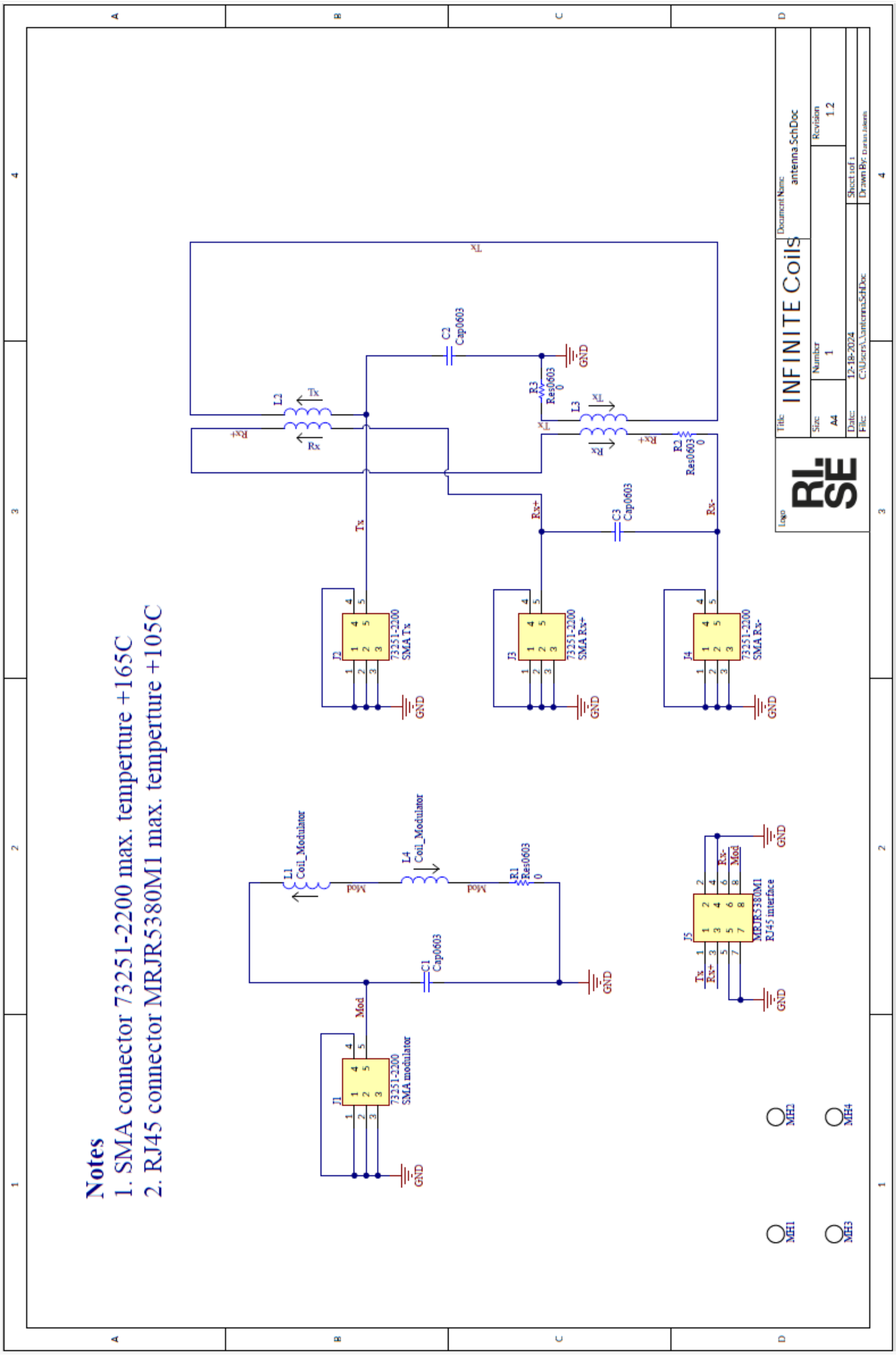

Figure 57 Schematics of the first version of the planar low frequency reader.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

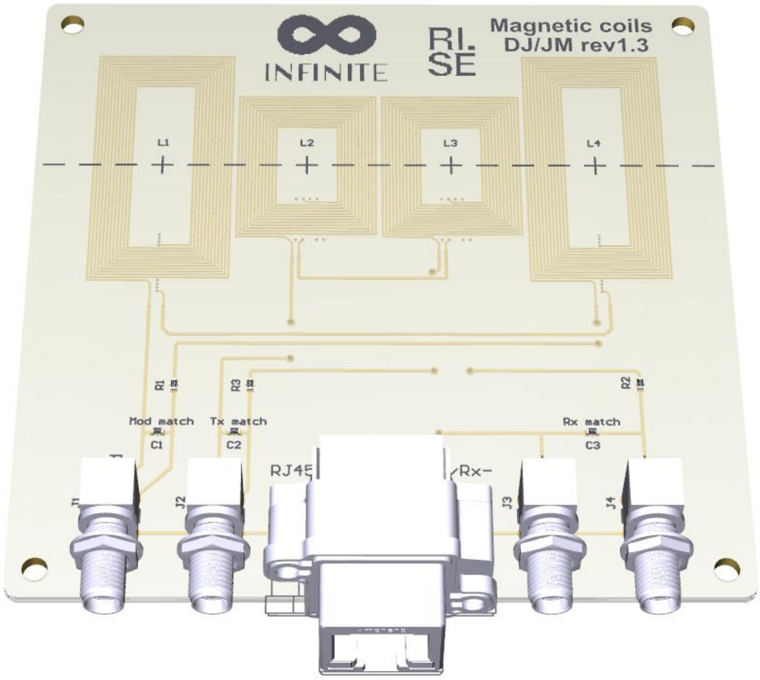

Figure 58 3D picture of version 1.3 of the planar low frequency reader.

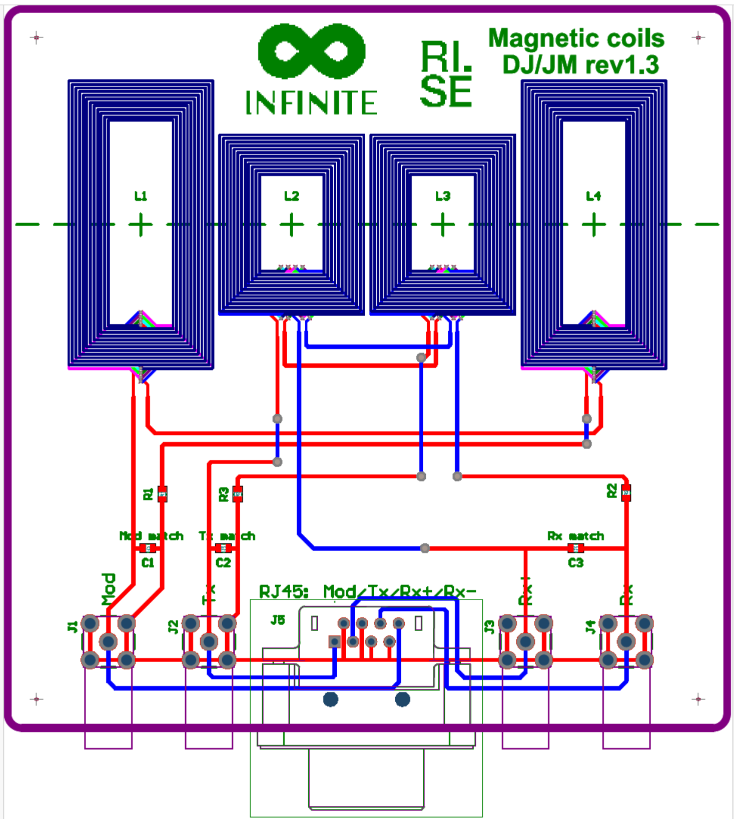

Figure 59 Overview of version 1.3 of the planar low frequency reader.