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Test bench for calibration of magnetic field sensor prototypes for COMPASS-U tokamak

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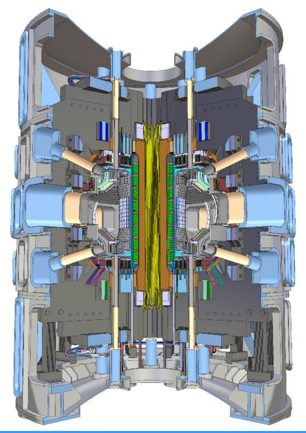
COMPASS-U Tokamak

- Will replace COMPASS at IPP, Prague [1]
- First plasma expected by 2023
- Metallic first wall device
- Closed high density divertor
- Hot-wall operation **300 - 500 ºC**
- Passed Conceptual design review in October 2018

I_p [MA]	2
R_0 [m]	0.89
a [m]	0.27
B_0 [T]	5
NBI P_{aux} [MW]	4
ECRH P_{aux} [MW]	4
t_{pulse} [s]	<5



Focus on the handling of DEMO relevant, extreme plasma heat fluxes.

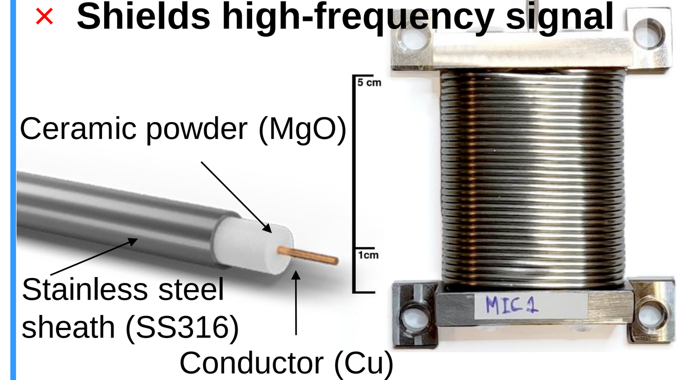
Local magnetic field sensors for Compass-U

In-vessel sensors should be compatible with 500 ºC operation. Due to being crucial for feedback and not easily accessible, part of the sensors should have high levels of reliability and availability. A thorough validation of the technological solutions chosen should be carried.

Mirnov coils (MIC)

Mineral Insulated Cable [2] coiled around stainless steel rods. Single layer and double layer prototypes built in-house.

✓ Survivability of more than 700 ºC
× **Shields high-frequency signal**

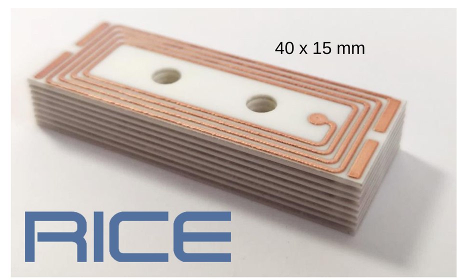


Fast coils

- Bare coper wire wrapped on ceramic mandrel
- Developed by PPPL based on NSTX Mirnov coils
- Intended up to 500 ºC

TPC sensors

- Thick Printed Copper technology
- Stacked layers with interconnected Cu track on ceramic substrate.
- Tested up to 500 ºC

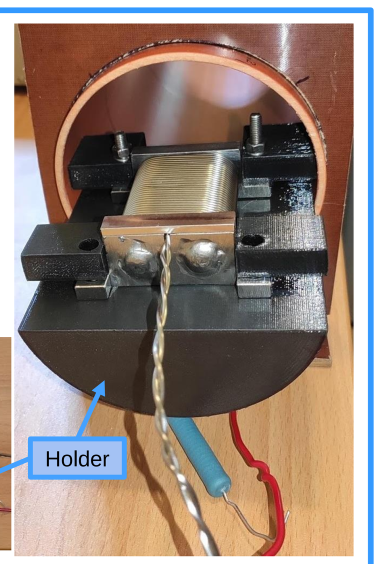


Mirnov coils are expected to have a low bandwidth due to the metallic shielding which is not present on Fast coils and TPC sensors.

How can we systematically calibrate the sensitivity of all sensors?
Up to which frequency can the sensors be used?

Effective area measurement

Sensitivity of an inductive sensor is proportional to its area. In order to determine the effective area one needs a source of homogeneous, changing magnetic field. For this purpose, a long solenoid was constructed. Due to the simple geometry, the magnetic field dependence on the current is well known and homogeneous.

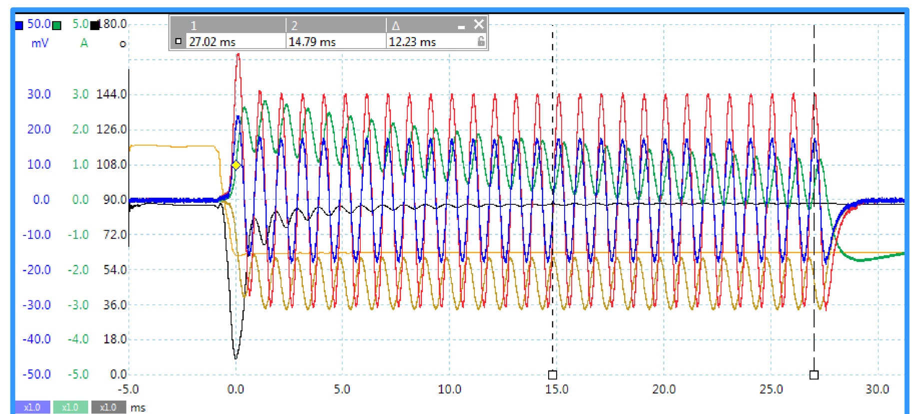


Long solenoid for low frequency effective area measurement
- 150 turns in two layers
- L = 4.2 mH
- B/I = 0.654 mT/A
- 58 mm central region with < 1% non-uniformity

$$V_0 = -S_{eff}\dot{B}$$

Driven by Kepco amplifier
- 100V, 2A
- 100 Hz - 5 kHz sine wave inputs
- Current measured on a 2 Ω resistor

Custom 3D printed holder alignment of sensor inside solenoid
- Designed for Mirnov coil prototypes
- 3D printed adaptors for smaller coils

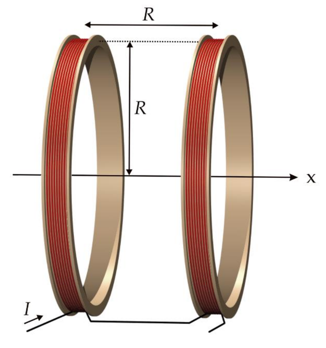


RMS value of harmonic signals is used to compute S_{eff}.

Uncertainties under 0.3 % reached. Deviation from design of ~1% obtained for TPC sensors

Frequency response measurement setup

Measuring the frequency response of the coil prototypes to local magnetic field requires the knowledge of a precise magnetic field source. A **Helmholtz coil** generates a nearly uniform magnetic field in its central volume, proportional to its current.
However, as its impedance increases with frequency it is challenging to generate and precisely measure the driving current on the span of 1 kHz – 1MHz on the same setup.

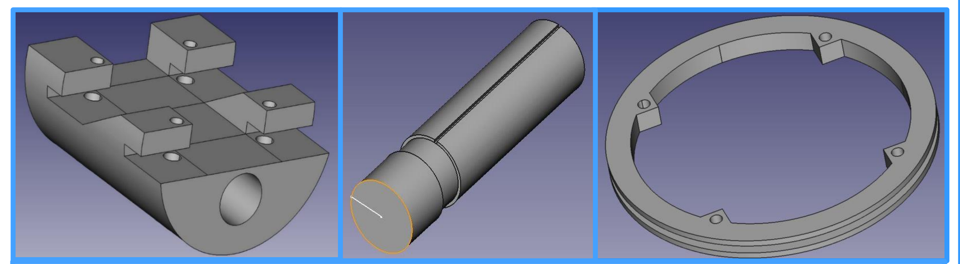


A bespoke Helmholtz coil was designed with the following requirements:
- Uniform ($B/B_0 > 99$ %) central area of 6 cm
- That would produce a readable output on a sensor with 50 mm² area
- Commercially available and inexpensive power source for driving

$$B_0 = \left(\frac{1}{5}\right)^{3/2}\frac{\mu_0 n}{R}\, I$$

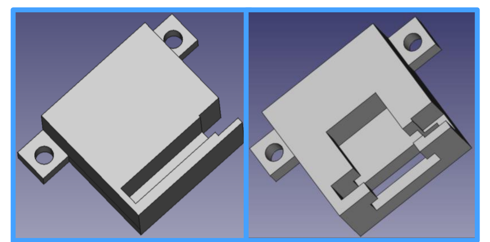
Helmholtz coil for frequency response
- 5 turns, 100 mm radius
- L = 27.4 μH
- B/I = 44.96 μT/A

Driven by Siglent 10 W amplifier
- 5 Ω shunt resistor in series
- 2.2 A max, 10x voltage amplification



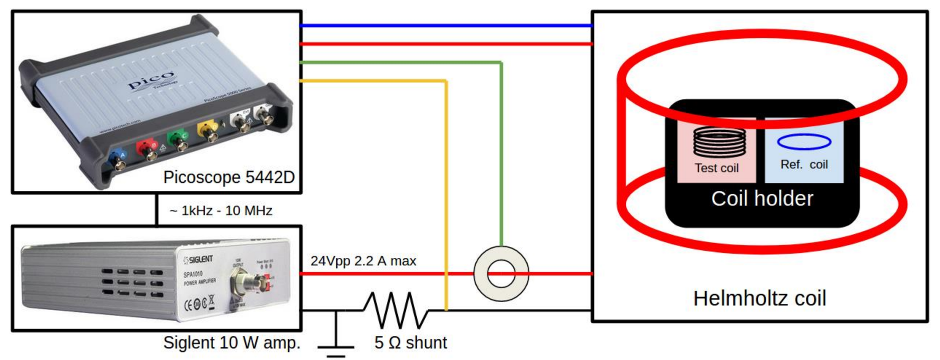
3D printed (PLA) parts: Coil holder with reference coil slot (left); Matching reference coil core (middle) and Helmholtz coil structure (right).

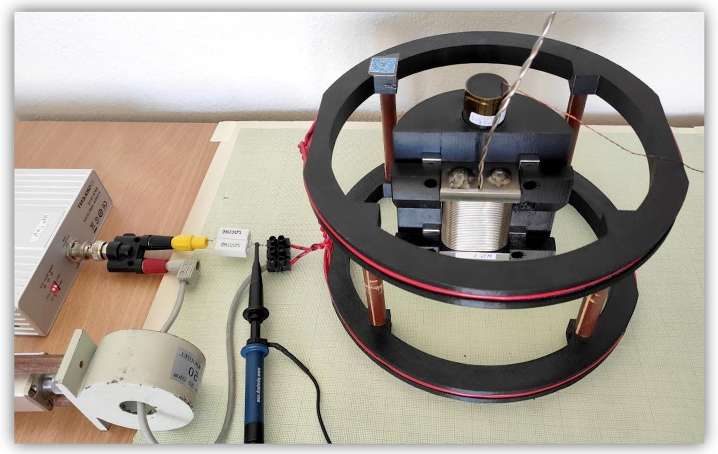
3 Response measurement methods
- Helmholtz current through shunt voltage drop. Used for f < 100 kHz.
- Normalization to low inductance reference coil (relative measurement. Used for f ≥100 kHz. Self resonant frequency outside of measurement frequencies.
- Rogowski coil for measurement of Helmholtz current. Used only for additional verification as is not as precise for low frequencies and has its own resonance bellow 1 MHz.



TPC sensor (left) and fast coil (right) 3D printed adaptors ensure coils are centered on Helmholtz coil. Fast coil adaptor designed for for both tangential and perpendicular directions.

Signal generation and measurement with PicoScope 5442D digital oscilloscope
- 12 bit measurement with automatically adjusted range and sampling timebase, ensuring 12 periods
- Amplitude and phase measurements using real-time fitting of the acquired waveforms





Two goals: (i) Measure MIC coils frequency response at feedback relevant frequencies; (ii) Measure and verify resonant effects in wide bandwidth local sensors.

Summary

- Achieved a low cost experimental setup by fully exploiting the functionalities of digital oscilloscope and making use of 3D printed parts.
- Automatized process makes it easy to verify frequency response of future prototypes or after thermal cycling tests are conducted.
- Measured sensitivity, bandwidth, introduced delay and resonance frequencies of coil prototypes at room temperature.
- With an electrical model where the individual proprieties are known, the effect of high temperature on frequency response can be estimated, without the need to generate precise magnetic fields on a high temperature chamber.

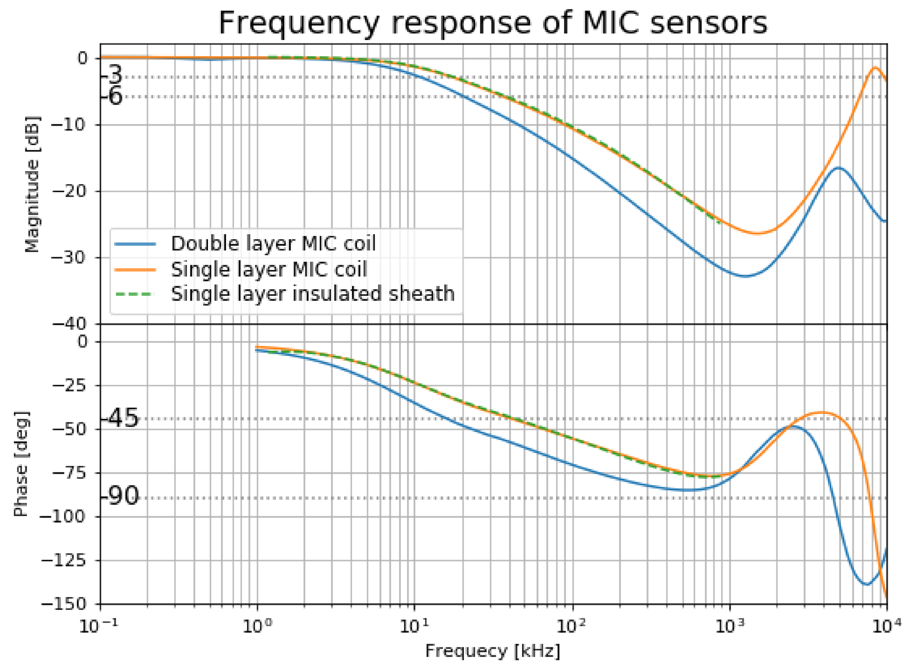
Mirnov coils frequency response

2 MIC coil geometries tested show a tradeoff in effective area and bandwidth:

Double layer S_{eff} = 410 cm²; $F_{(-3\ dB)}$ = 11 kHz
Single layer S_{eff} = 175 cm²; $F_{(-3\ dB)}$ = 17 kHz

Breaking the conduction between the steel sheaths of each turn and to the central core of the coil did not improve the bandwidth.

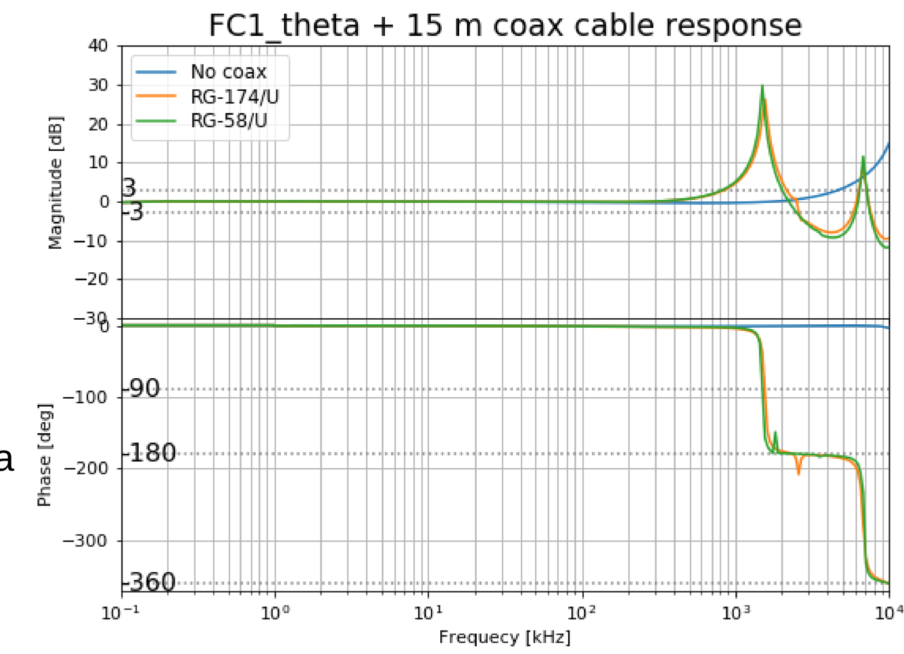
Further prototypes are being designed aiming at mitigating the observed attenuation. These will be based on the sturdier 2-layer design.

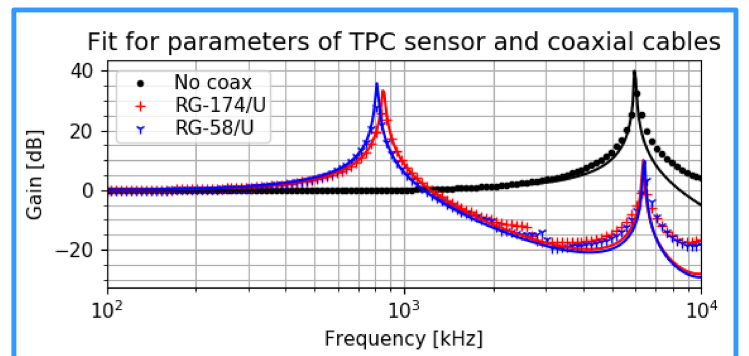


MIC Mirnov coils show bandwidths on the 10-20 kHz range

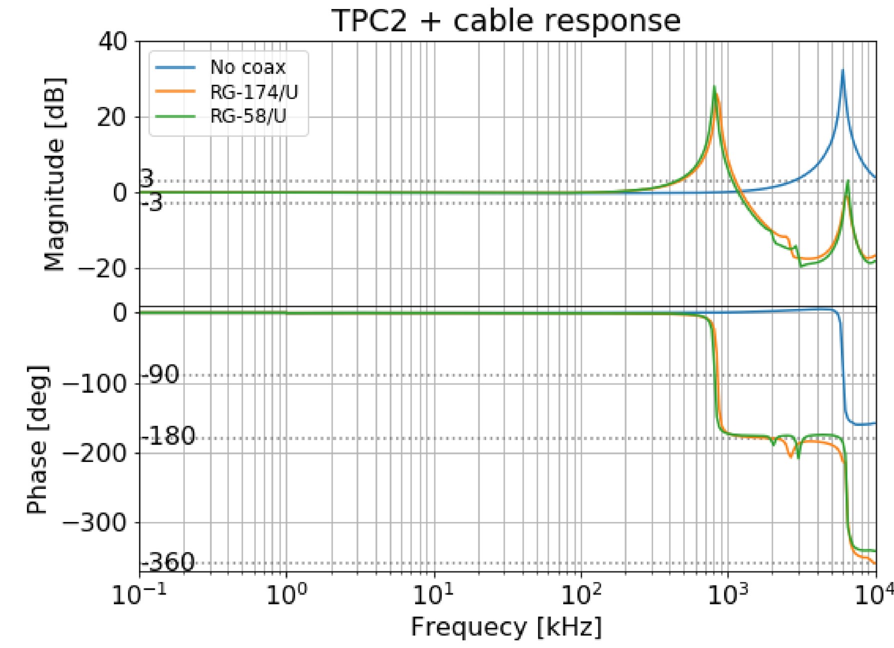
Fast coils and TPC sensors frequency response

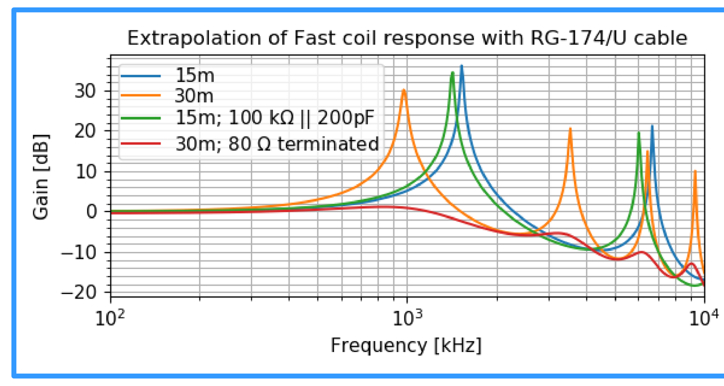
Both Fast coils and TPC sensor show **negligible attenuation up to 1 MHz**.
However, high frequency signals propagate as waves in the long transmission line. Due to the high input impedance of the data acquisition, these waves can be reflected and create standing waves at given frequencies, causing **resonances**. The frequency of these resonances depends on the electrical parameters of sensor, transmission line and data acquisition and It is important they do not interfere with plasma oscillation measurements.





Resonances fit for cable parameters and probe parallel capacitance. Mismatch after 1 MHz attributed to experimental setup. Estimated capacitance in line with precise measurements carried out at RICE.





Using the measured parameters, extrapolations can be made for different lengths of cable and input impedances of DAS. Low probe and DAS capacitances ensure plasma oscillations up to 600 kHz can be accurately measured.

Measured frequency response allowed calibration of electrical model of probe + cables + scope input impedance, accurately predicting resonance frequencies

References

[1] Panek R., et al., “Conceptual design of the COMPASS upgrade tokamak”, Fusion Engineering and Design 123, 11-16 (2017).
[2] Torres A., et al., “Mineral insulated cable assessment for inductive magnetic diagnostic sensors of a hot-wall tokamak”, Journal of Instrumentation 14, C09043 (2019).

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