Mineral insulated cable assessment for inductive magnetic diagnostic sensors of a hot-wall tokamak

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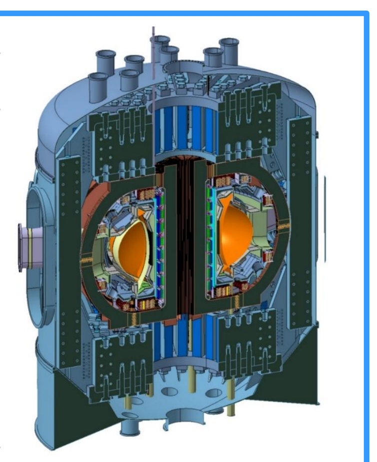
COMPASS-U Tokamak

- Will replace COMPASS at IPP, Prague [1]
- First plasma expected by 2022
- Metallic first wall device
- Closed and well diagnosed high density divertor
- Hot-wall operation **300 - 500 °C** with baking at higher temperatures

Parameter	Value
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]	>= 2



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

Constraints for magnetic diagnostic

- Beyond survivability, coils should provide reliable and accurate measurements at high temperatures
- In addition to the actively heated vacuum vessel, the planned ECRH will increase the temperature locally even further
- Strong mechanical forces during disruptions.
- MIC considered for low-frequency signals (equilibrium reconstruction, control) show cut-off frequencies in the range of **50-200 kHz** [2]
- Limited space for the ex-vessel coils
- Delay introduced in the control loop should be minimized

Mineral Insulated Cables (MIC)

- ✔ Survivability of more than 700 °C
- ✔ Well-established use in tokamaks (DIII-D, TCV, JET, KSTAR, TEXTOR)
- × **Shields high-frequency signal**
- × Risk of outgassing if damaged
- × Challenging vacuum termination under high temperatures

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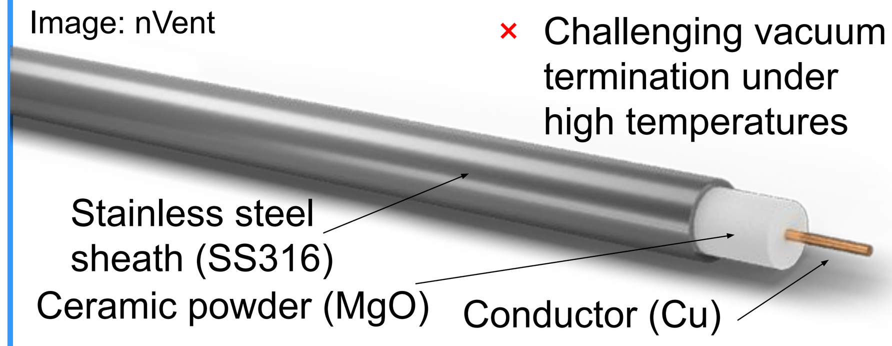


MIC	Manufacturer	$Ø_{outer}$ [mm]	$Ø_{core}$ [mm]	Shielding thickness [mm]
A	Thermocoax (FR)	0.5	0.2	0.10
B	Thermocoax (FR)	1.0	0.45	0.12
C	ARi Industries (US)	1.5	0.305	0.1524
D	Sukegawa (JP)	1.6	0.53	0.22
E	Thermocoax (FR)	3.0	0.45	0.39*
F	MICC (CN)	3.0	0.45	0.45
G	Sukegawa (JP)	3.2	0.85	0.37

*estimation

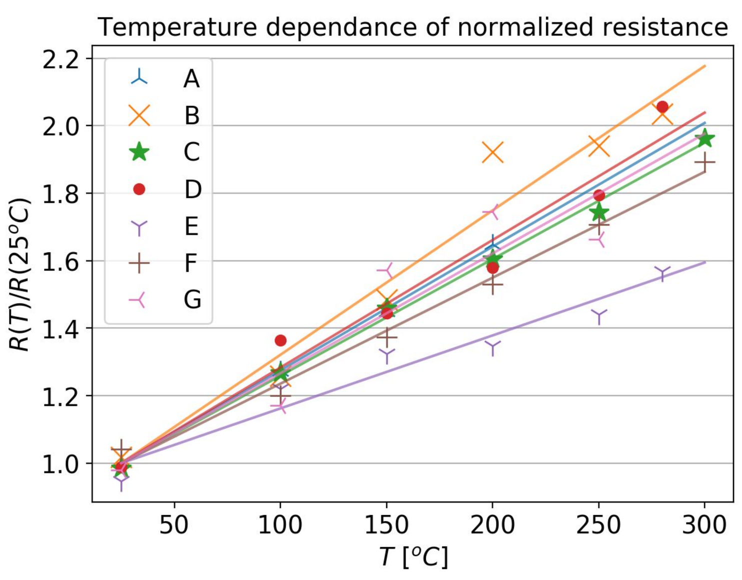
High temperature signal transmission tests

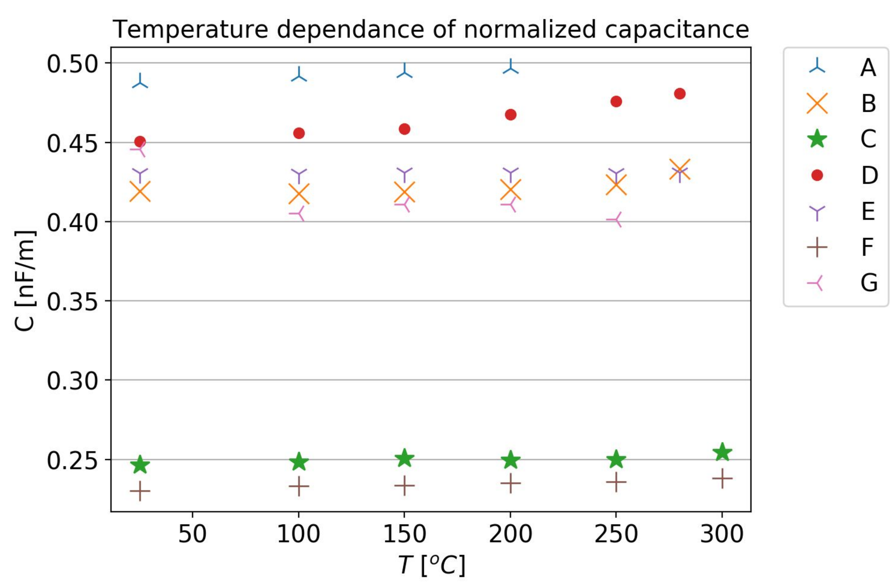
- 10m long MIC coiled inside an oven reaching 300 °C
- Signal generator used to measure cut-off frequency of the cables as transmission lines.

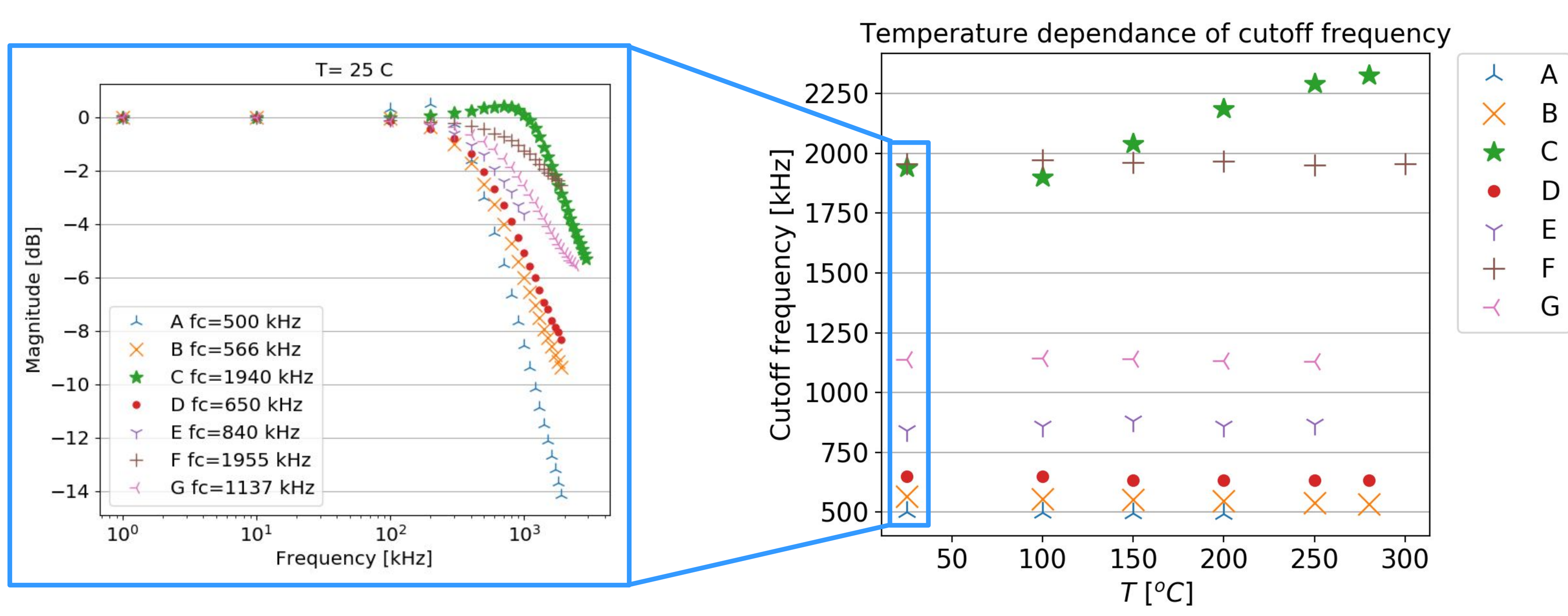
Temperature coefficient α
$R(T) = R(T_0)(1 + \alpha\,\Delta T)$
Reference for copper: $4.04 \cdot 10^{-3}$ K^{-1}

Cutoff frequency f_c (for signal transmission)
Half power point (-3 dB)

MIC	R (25°C) [Ω/m]	α [10^{-3} K^{-1}]	C (25°C) [nF/m]	F_c (25°C) [kHz]
A	0.727	4.0 ± 0.1	0.49	500
B	0.231	4.8 ± 1.0	0.42	566
C	0.356	3.8 ± 0.2	0.25	1940
D	0.090	4.2 ± 0.7	0.45	650
E	0.031	2.3 ± 0.4	0.43	840
F	0.122	3.4 ± 0.3	0.23	1955
G	0.442	3.9 ± 1.4	0.45	1137





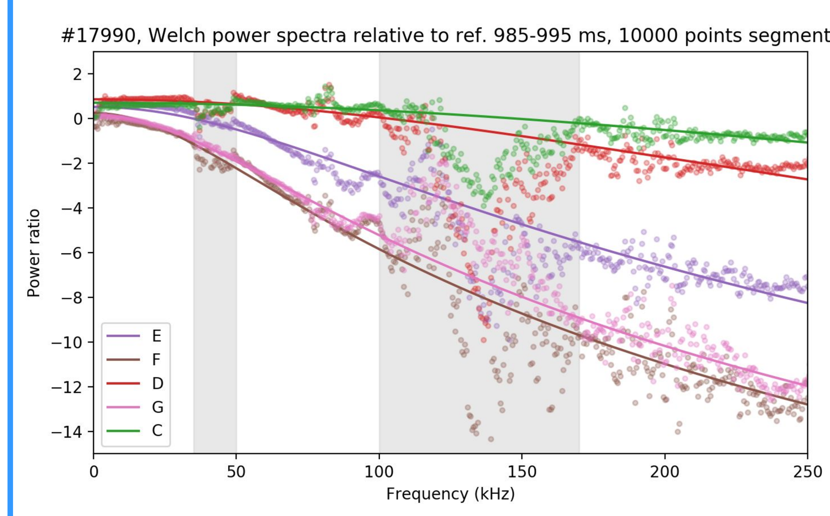


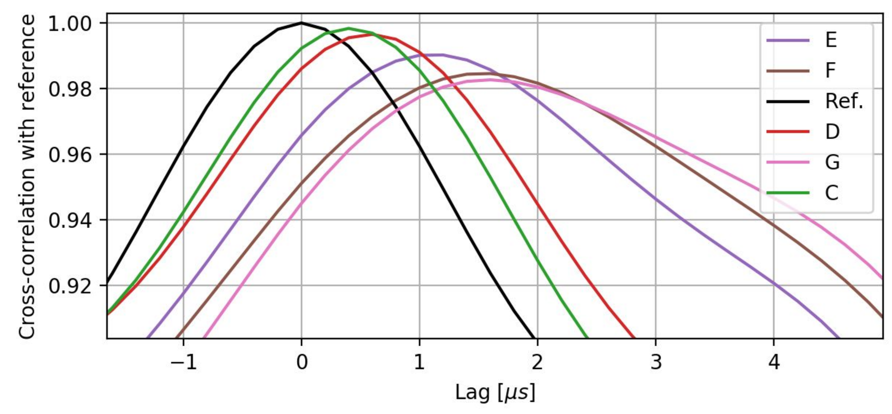
Capacitance and frequency response approximately constant for temperatures relevant for the first phase of COMPASS-U operation. Resistance scales linearly and can double at 300 °C

MIC flux loop tests

- Tests performed on COMPASS tokamak using real plasma as source of magnetic signal
- Equatorial ex-vessel single loops using MIC and reference copper wire with comparable geometry
- MIC shielding penetration filtering determined by the ratio of the power spectra (Welch method) and fit of first order filter
- Delay estimated using cross-correlations

MIC	F_c [kHz]	Delay [μs]
A	Not tested	Not tested
B	328 ± 9	0.2 ± 0.1
C	335 ± 3	0.2 ± 0.1
D	220 ± 2	0.3 ± 0.1
E	92.8 ± 0.5	1.3 ± 0.1
F	64.8 ± 0.7	1.8 ± 0.1
G	69.8 ± 0.5	1.8 ± 0.1





Frequency response comparable to first order filter: only shielding effect
Cut-off strongly dependent on shielding thickness but independent on manufacturer

Induction tests on test coils

Test coils with effective area similar to conceptual design coils: 22 turns, $Ø_{core}$ = 27 mm, l_{coil} = 80 mm, MIC twisted pair

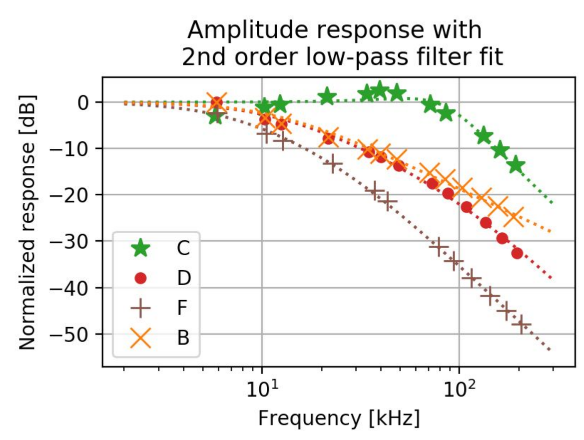
Magnetic field generated by solenoid driven by RLC circuit generating damped oscillations: L= 32 μF, C= 33nF – 30 μF, **f = 5 – 200 kHz**

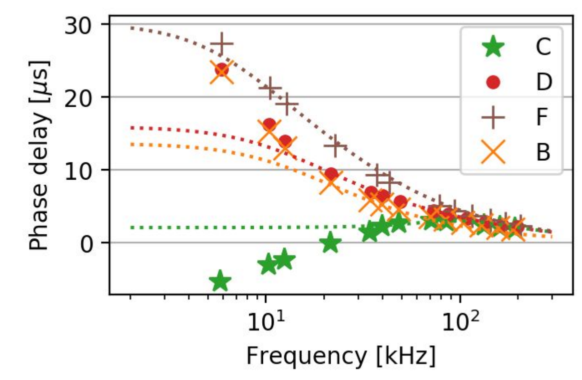
Frequency response obtained by the ratio of amplitudes (damped harmonic fit) on the coil voltage V_c and current on the solenoid I_s

$$V_c = -\frac{d\Phi}{dt} \propto \omega I_s$$

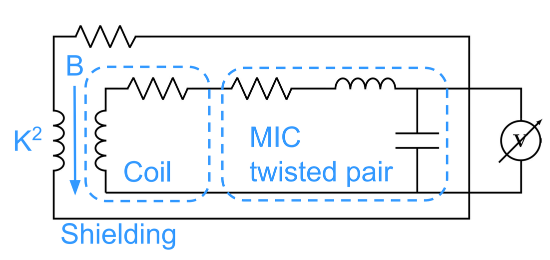
Frequency response fits second order filter behaviour controlled by the shielding, with a resonance appearing on MIC C (Q=0.9)

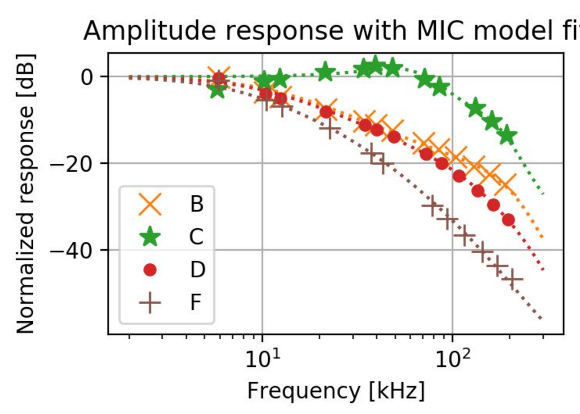
Applied model in **Strait E. J., (1996) [3]** modeling the coil with shielding and transmission line with different characteristic times





Model takes into account the eddy currents on the shielding. Fit for the coupling coefficient between coil and shielding **K^2** and the twisted pair L and C.





With the fitting results the model can be used to predict the behaviour of prototype coils and use the geometry of the coil and impedance of external circuit to extend the passband

Conclusions and outlook

- For signal transmission, temperature does not affect frequency response but only resistance. The measured resistance variation with temperature will be accounted for on the design of data acquisition system.
- The cut-off frequencies above 1MHz for 10m long cables proves MIC can be a solution to lead signals of electrical probes and other in-vessel diagnostics.
- Phase delay of signals was measured for test coils, furthermore, the behaviour consistent with a second order low-pass filter allows the estimation of the delay introduced in the control loop.
- No major qualitative differences between the MIC of different manufactures were observed, being possible to attribute the behaviour to geometrical properties.
- Further work needs to be conducted in order to test prototype coils under higher temperatures (300-700) and under vacuum to ensure compatibility with COMPASS-U conditions, where differences between manufacturers can emerge.

References:

[1] Panek R., et al., “Conceptual design of the COMPASS upgrade tokamak”, Fusion Engineering and Design 123, 11-16 (2017).

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[3] Strait E. J., “Frequency response of metalclad inductive magnetic field probes”, Rev. Sci. Instrum. 67, 2538 (1996)

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