# Magnetic field modulation for space:

# from MELISA to ILIADA


X. Manyosa
V. Jiménez
J. Ramos
J. Pons
J. Estany
M. Domínguez

*UPC*

D. Roma
M. Arqué
B. Bonastre
V. Martín
J. Salvans
M. Nofrarias

*ICE-CSIC*

S. Gómez
A. Sanuy
J. Mauricio
D. Gascón

*ICCUB*



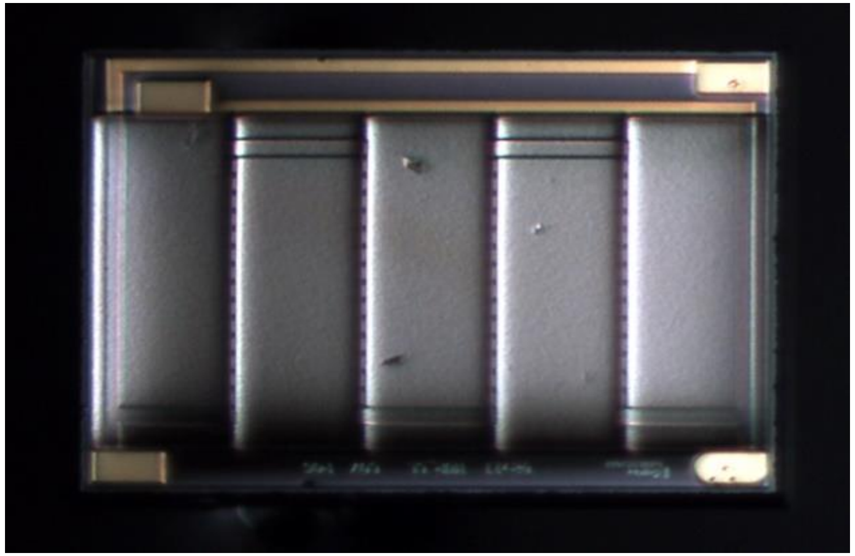
IEEC
Institut d'Estudis
Espacials de Catalunya

www.ieec.cat

# Target specifications of the sensor

- The target is to fulfill the requirements of the LISA diagnostics subsystem:
  - A low-power, miniaturized magnetometer with a very low noise floor:
    - $\mathbf{100}\ \boldsymbol{nT/\sqrt{Hz}}$ - $\mathbf{10}\ \boldsymbol{nT/\sqrt{Hz}}$
  - In the ultra-low frequency range
    - $\mathbf{0.1}\ \boldsymbol{mHz} - \mathbf{100}\ \boldsymbol{mHz}$

# Tunneling Magnetoresistance



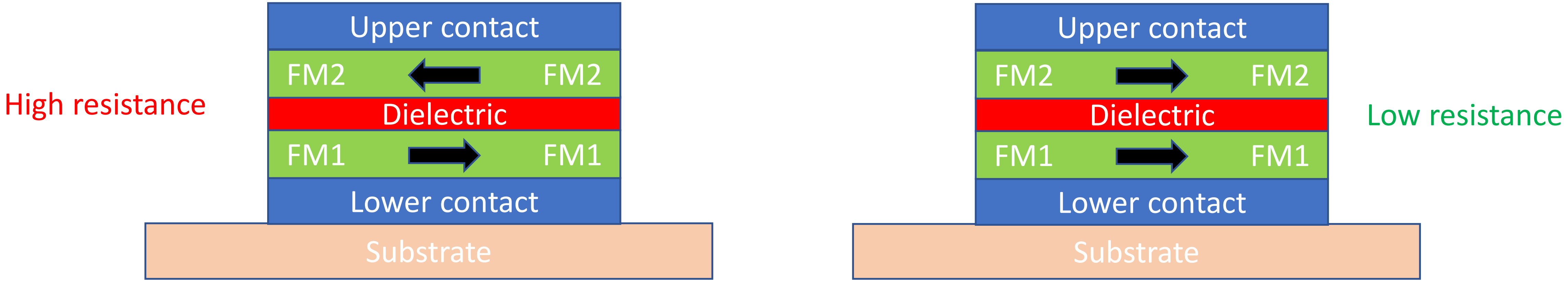
- Bare-die TMR9001 from Multidimension

  1 x 1.5 mm

- TMR are high sensitivity magnetic field sensors.

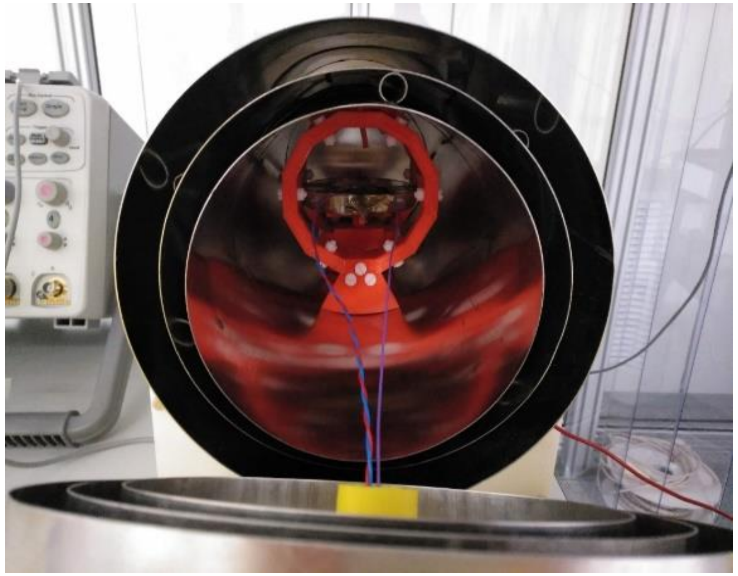
- Formed by multiple Magnetic Tunneling Junctions (MTJ) in series.

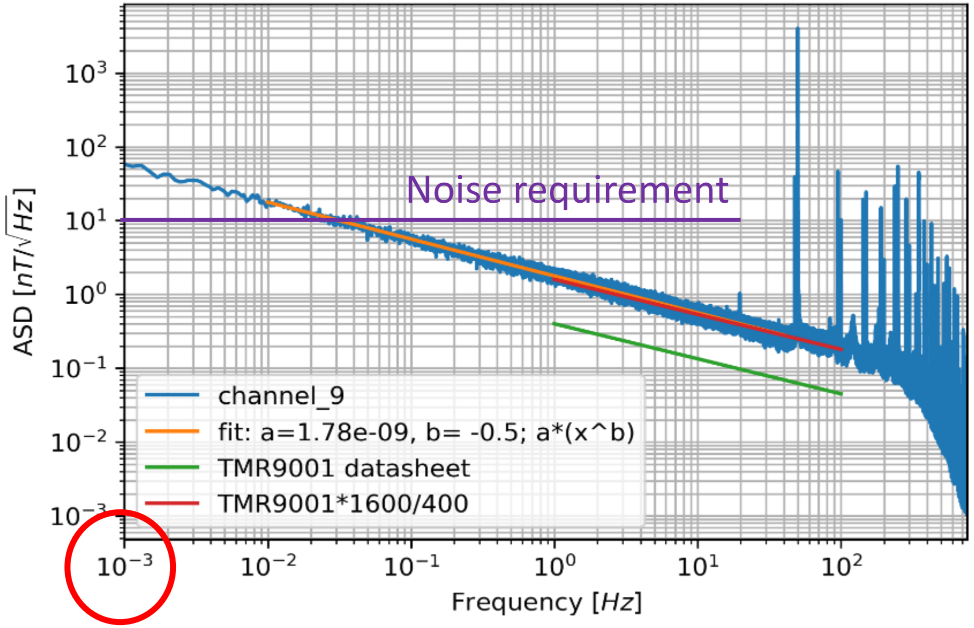
# MTJs




- Magnetic Tunneling Junction:
  - Formed by two ferromagnetic layers separated by a thin dielectric.
    - One layer with pinned spins (spins have a permanente orientation)
    - The other layer with free spins (follow the external magnetic field)
  - Spin-dependent tunneling (Julliere's model):
    - up-spin electrons only tunnel into up-spin states,
    - down-spin electrons only tunnel into down-spin states.
  - Therefore the resistance will depend on the magnitude and direction of the magnetic field.

# TMR noise characterization



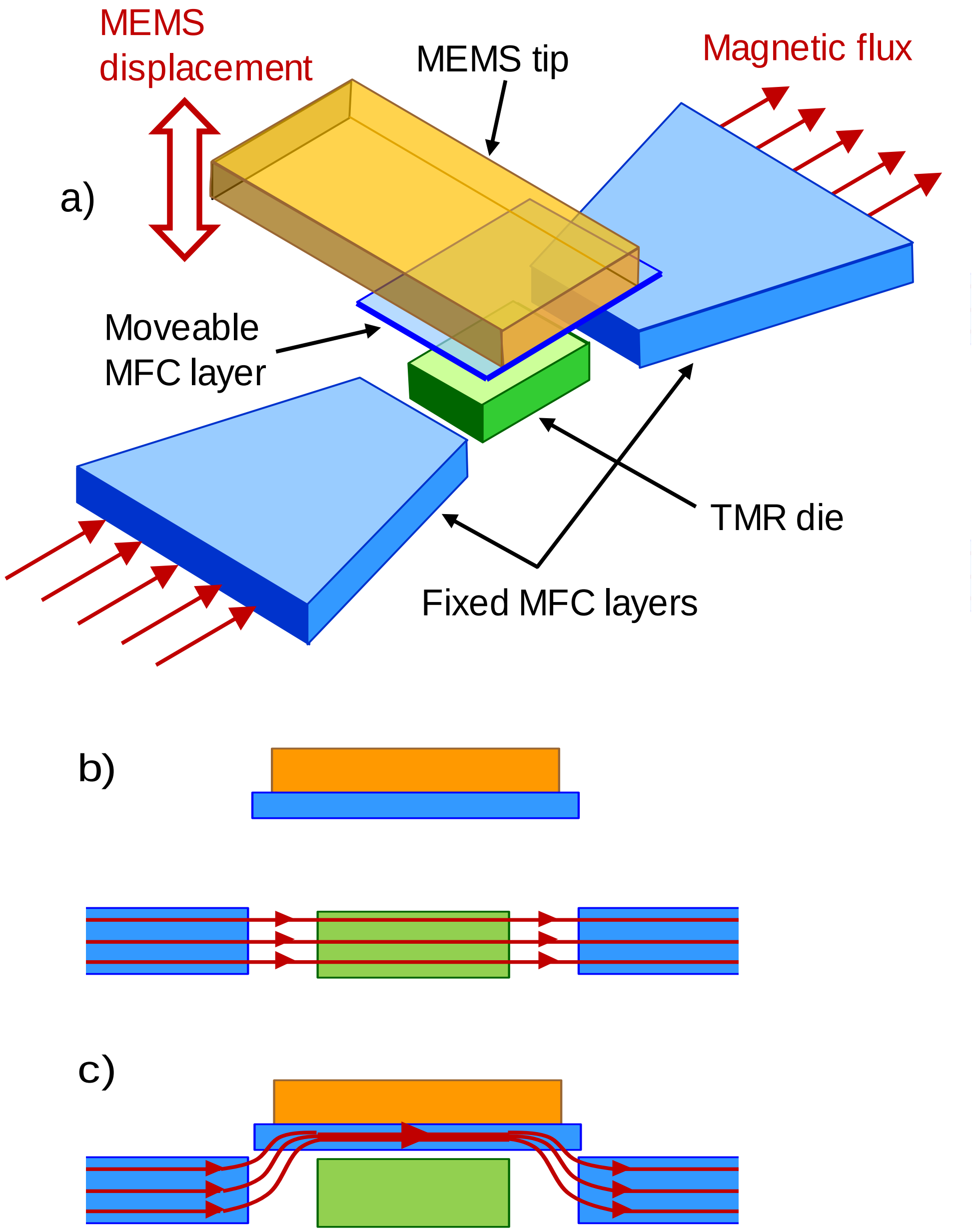



Noise floor requirement

- TMR is placed inside a mu-metal chamber in a temperature controlled environment.
- At these low frequencies, 1/f noise (flicker) noise is dominant.
  - *Large amplitud fluctuations 'happen' less often*.
- The TMR9001 from Multidimension **does not fulfill** the noise floor requirement…

# Magnetic Field Modulation

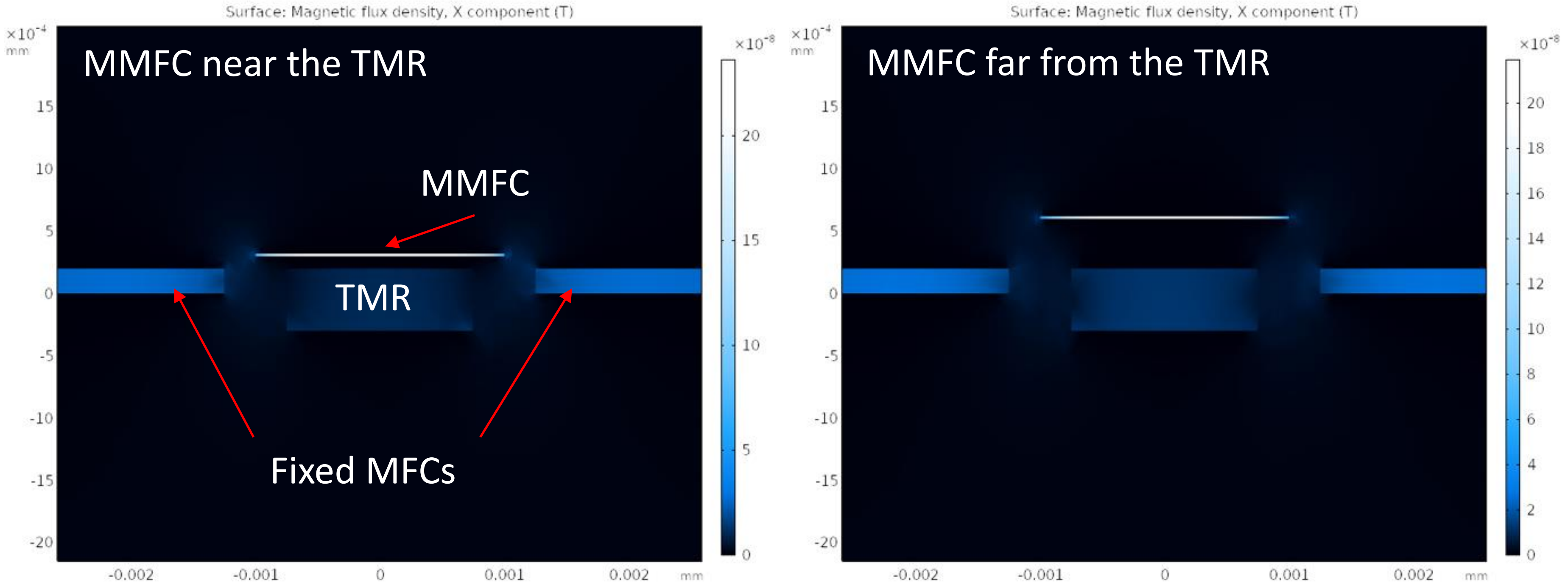
- We can move (up-convert) the signal to higher frequencies where flicker noise does not appear.
- Modulation with a Movable Magnetic Flux Concentrator (MMFC):
  - a) MMFC is far from the TMR sensor; local magnetic field at TMR almost undisturbed.
  - b) MMFC, which also includes a high-permeability layer, is close enough to the TMR sensor to “remove" most of the magnetic flux away.
- A Microelectromechanical System (MEMS) resonating will **modulate** the local magnetic flux at the TMR.
- Two fixed MFC layers increase field at TMR, and therefore its sensitivity.



# Magnetic Field Modulation

- FEM simulations proved that a ~**40% of modulation efficiency** can be obtained with:
  - 300 µm of MEMS displacement
  - > 15 µm of MMFC thickness

$$e = \frac{B_{max} - B_{min}}{B_{nf}} = \frac{1.52\ nT - 0.82\ nT}{1.8\ nT} = \mathbf{38.88\%}$$



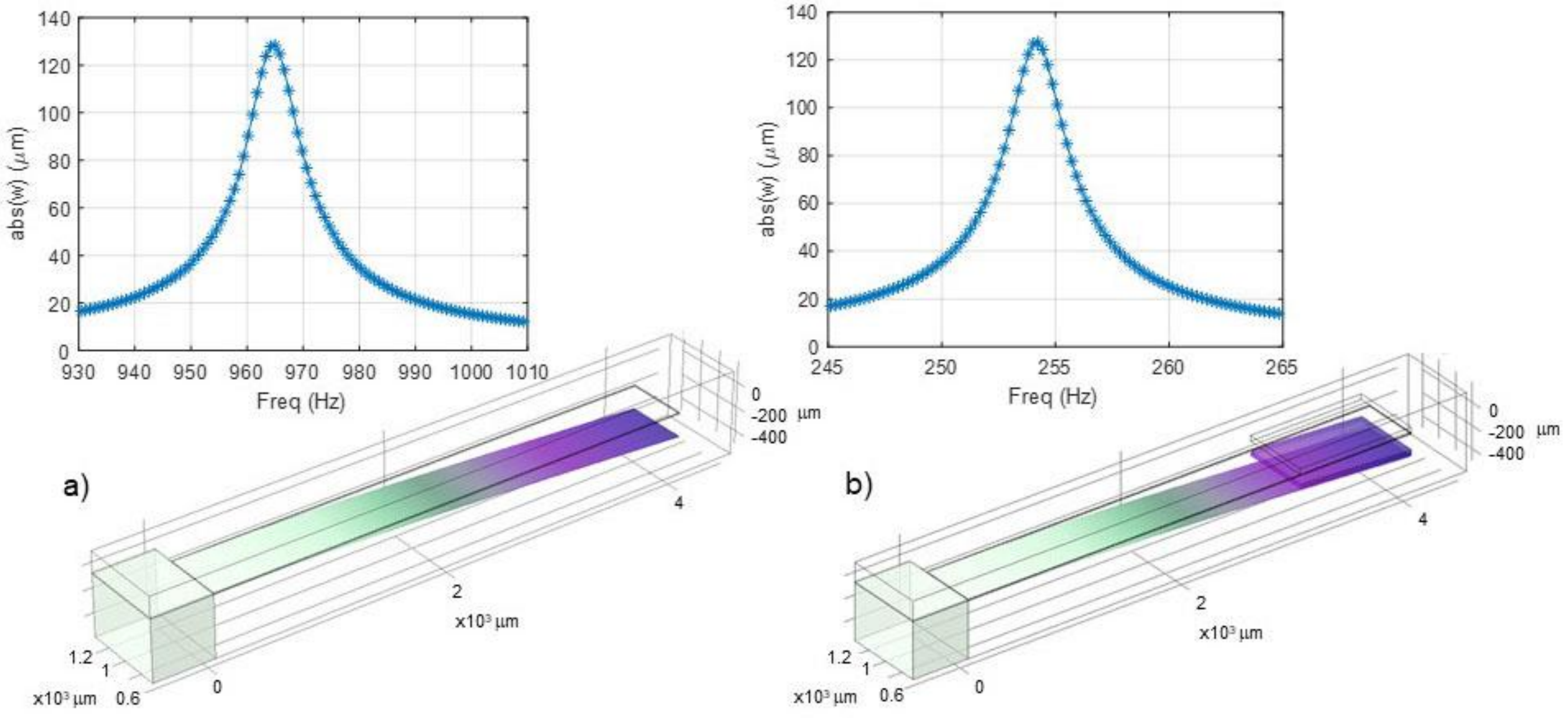

$B_{nf}$: *Magnetic field at TMR* ***without*** *MMFC*

$B_{max}$: *Magnetic field at TMR with MMFC* ***far*** *from it*

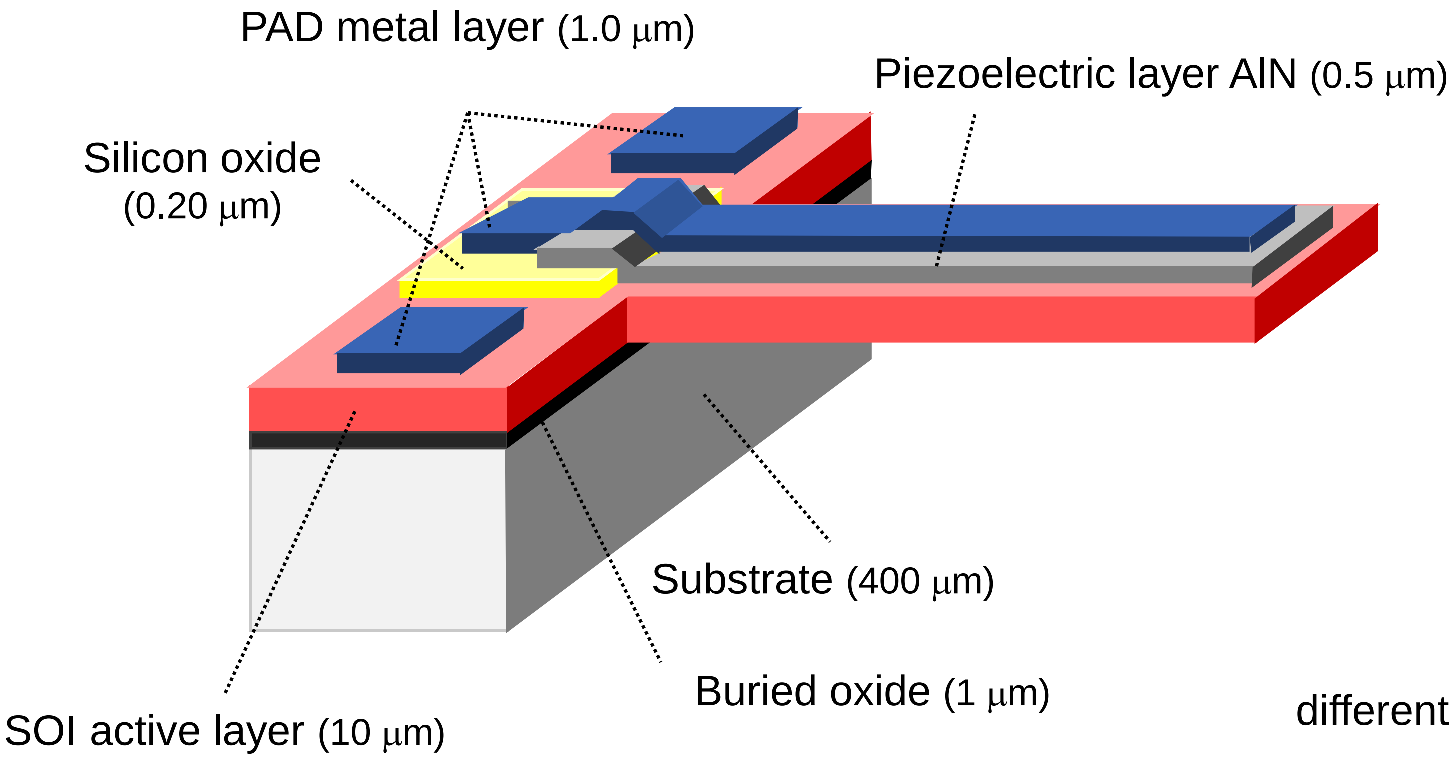
$B_{min}$: *Magnetic field at TMR with MMFC* ***near*** *it*

# MEMS resonators

- FEM simulations proved that displacements of that order of magnitude could be achieved with MEMS cantilever beam of 4 x 1 mm.
- And that their resonance frequencies would be around 960 Hz without the high permeability layer and around 250 Hz with it.



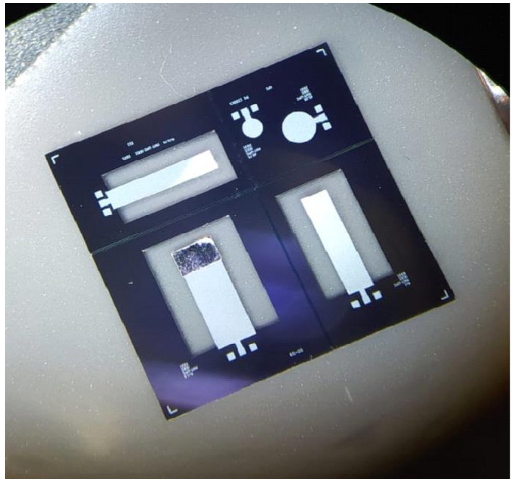
# MEMS resonators

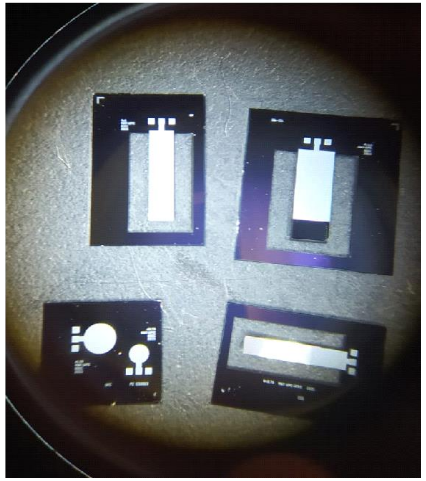


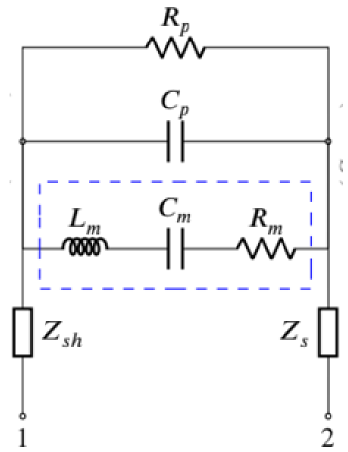

Devices #1 and #2
Cantilevers
Same length (4 mm),
different width (0.75 and 1 mm)

- PiezoMUMPS technology from MEMSCAP.
- SOI technology with piezoelectric actuation and sensing.
- Three cantilever designs.

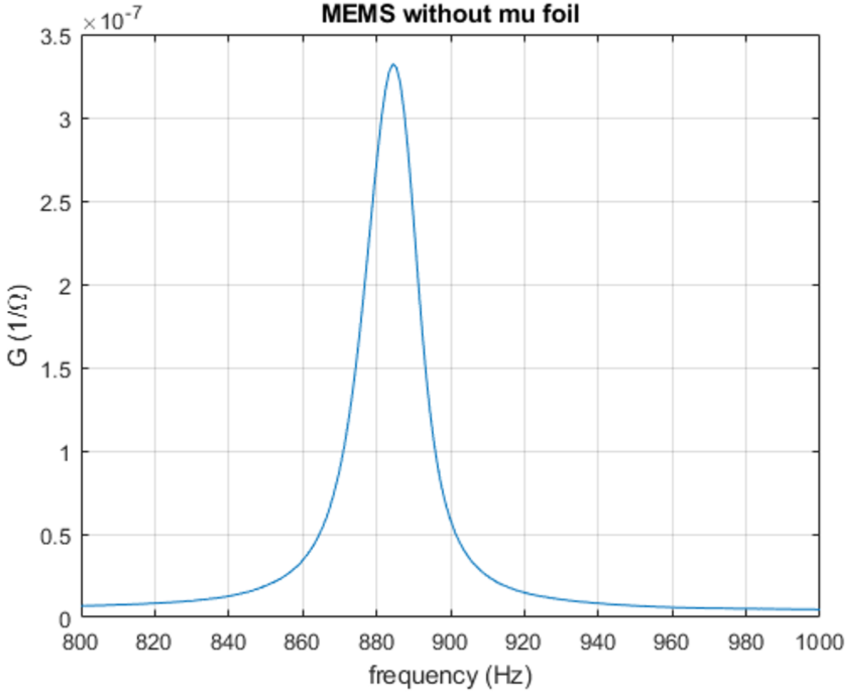
# MEMS resonators





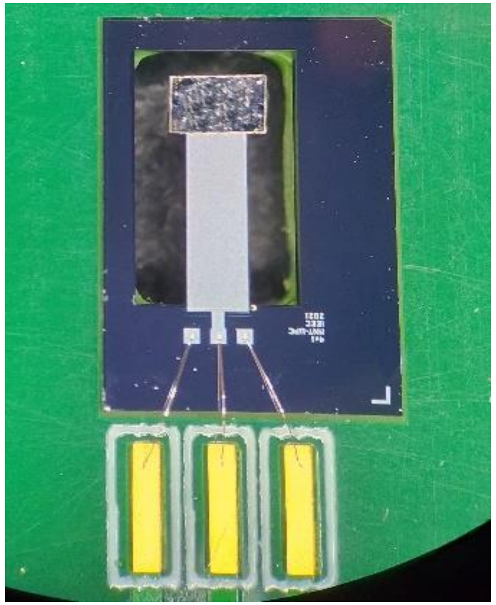


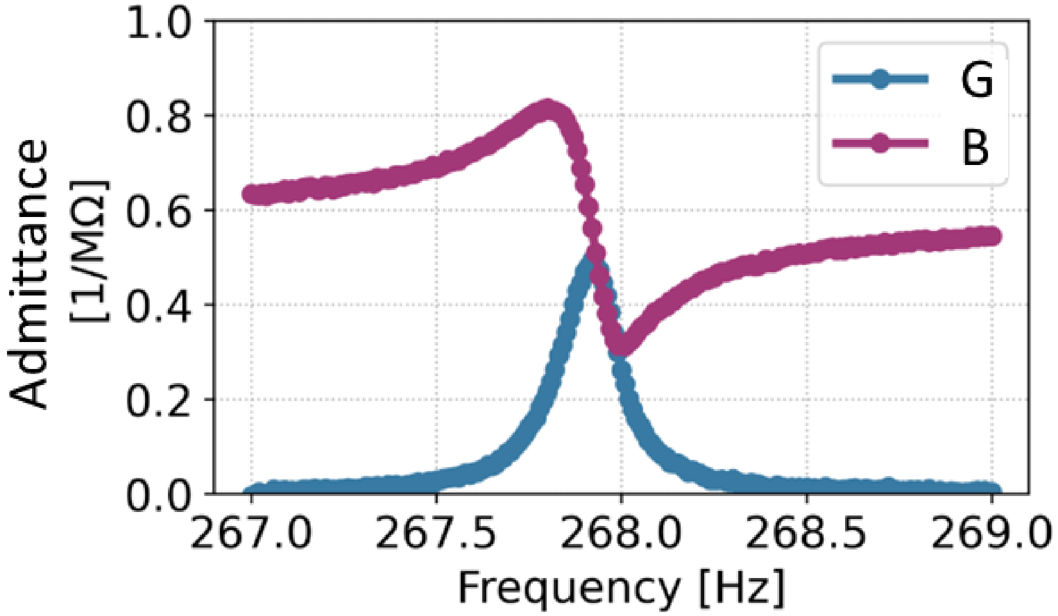

Electrical model




- Resonant frequencies in the 800-900Hz range.
- Quality factors:
  - Atmospheric pressure: ~ 100.
  - Low pressure: ~ 900.

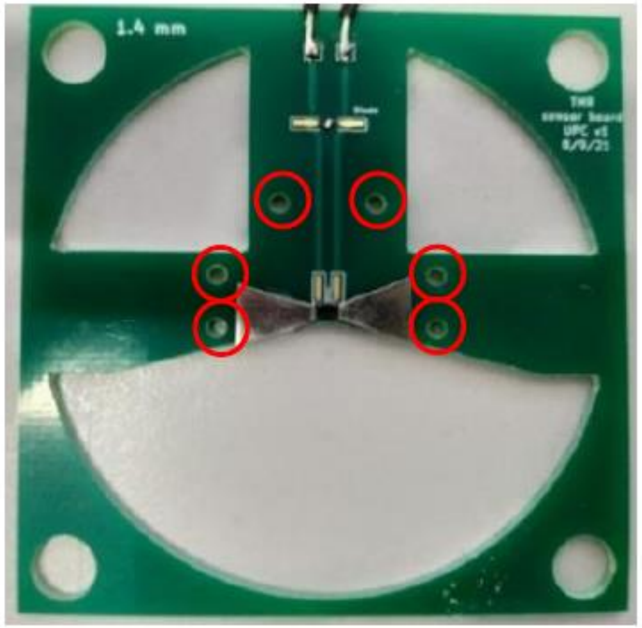
# Deposition of high permeability layer on MEMS



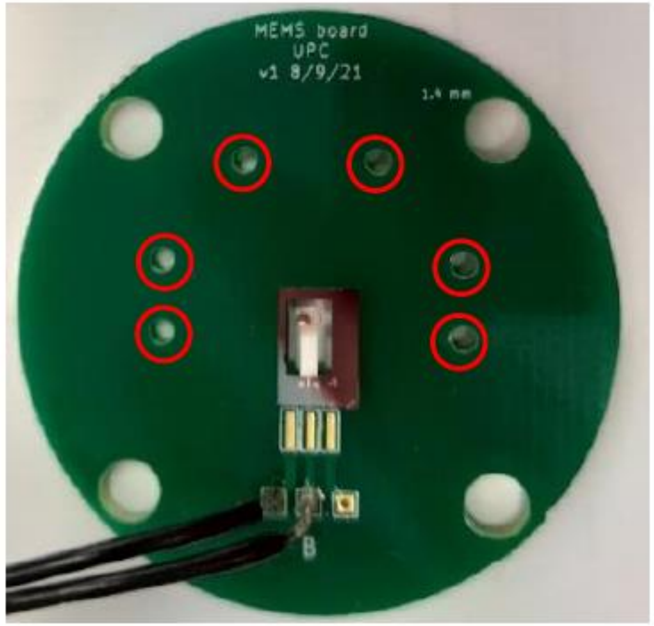



- Mu-foil with a thickness of 23μm deposited on top of the MEMS structure.
- Resonant frequency decreases: 240-280Hz.

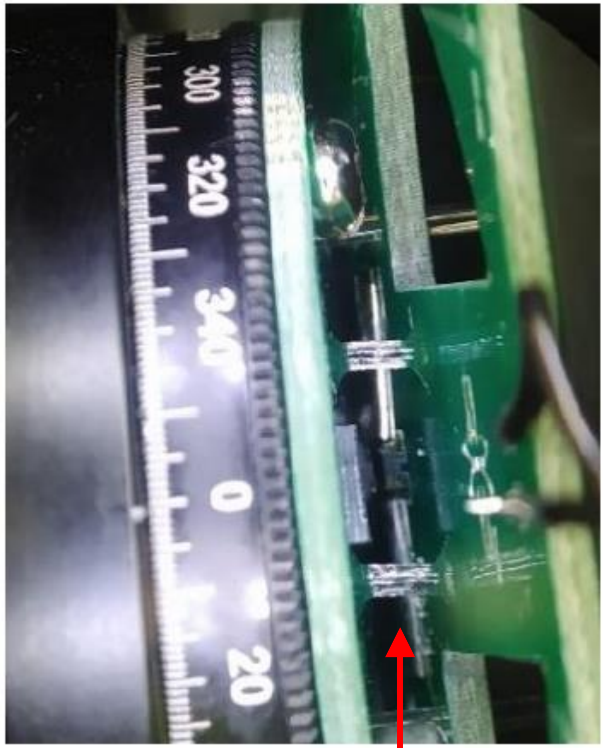
# Sensor Alignment and Assembly



TMR PCB



MEMS PCB

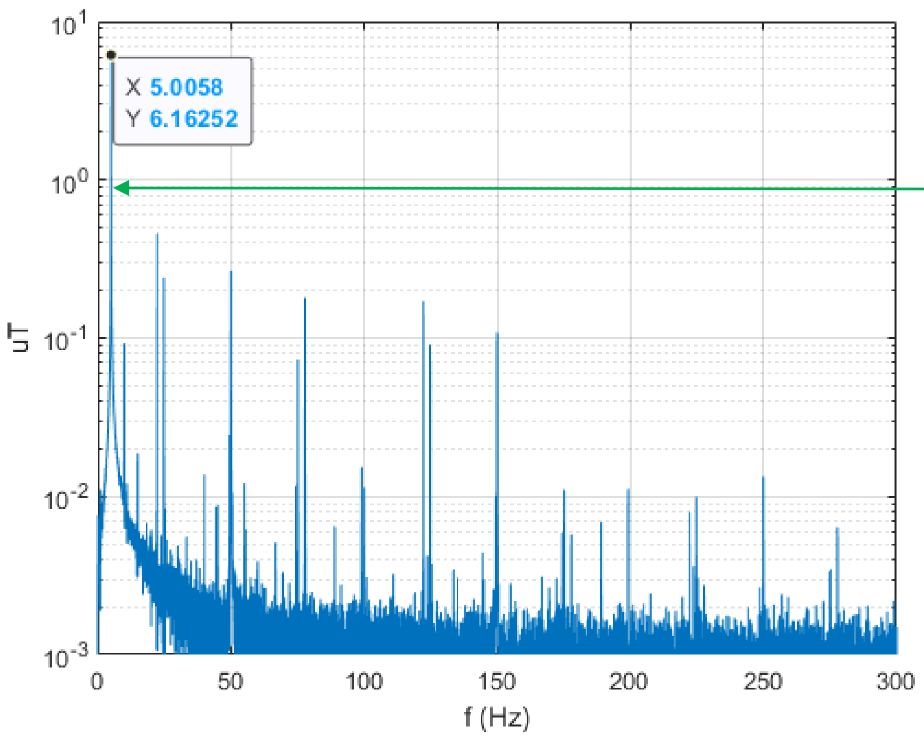


Quartz rods
Are used to align and fixate (with epoxy) the TMR and MEMS PCBs

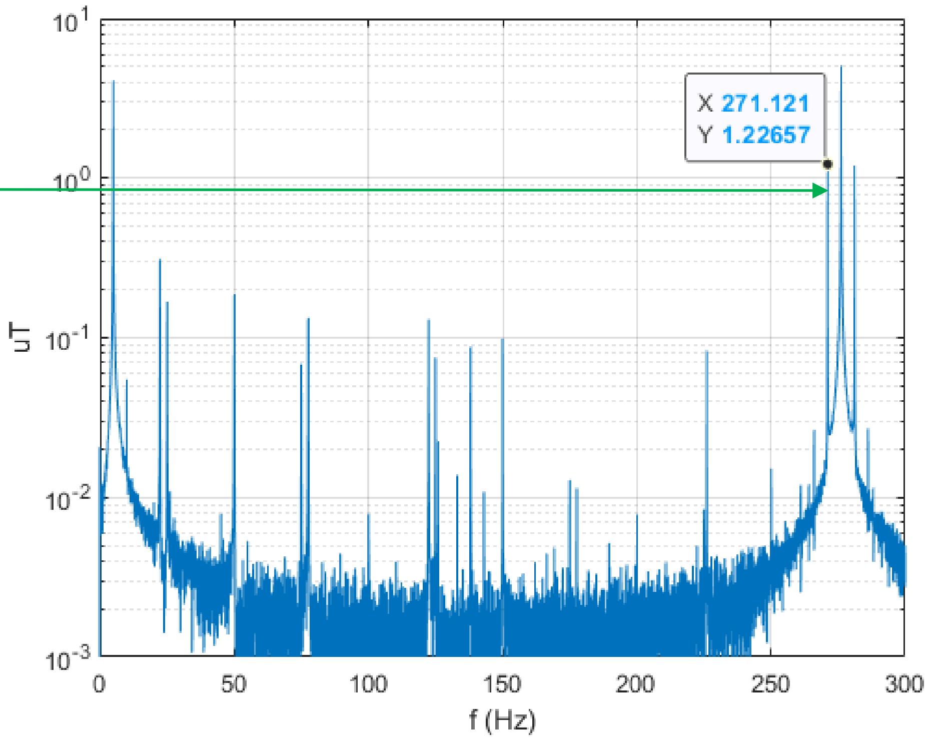
- MEMS present residual stress generating curvature.
- Alignement is made monitoring/optimizing modulation depth.
- Quartz rods and epoxy used to permanently fixate the system.

# Modulation efficiency

$$e = 2\,\frac{1.22\,uT}{6.16\,uT} = 39.61\%$$



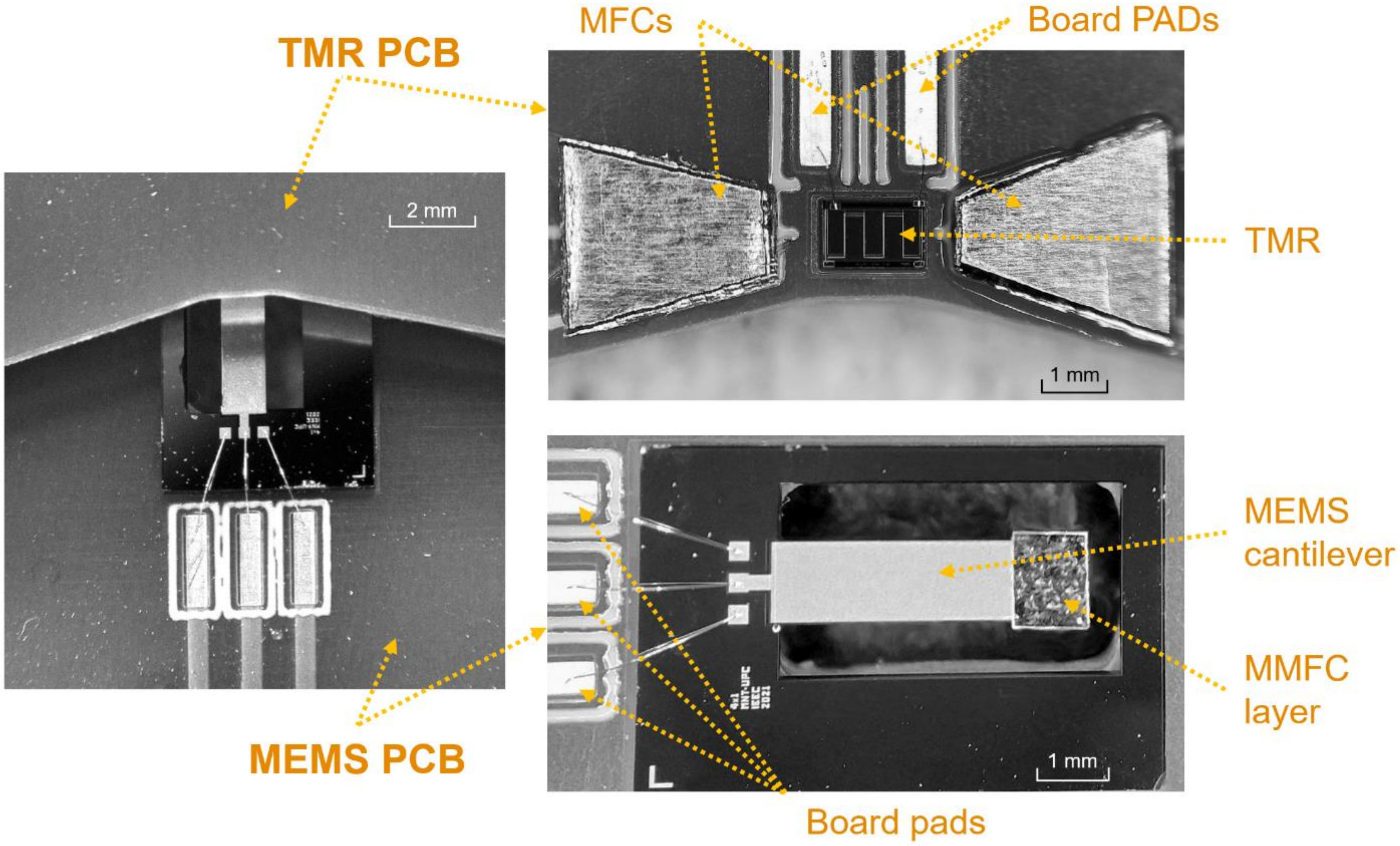

**TMR before MEMS assembly**



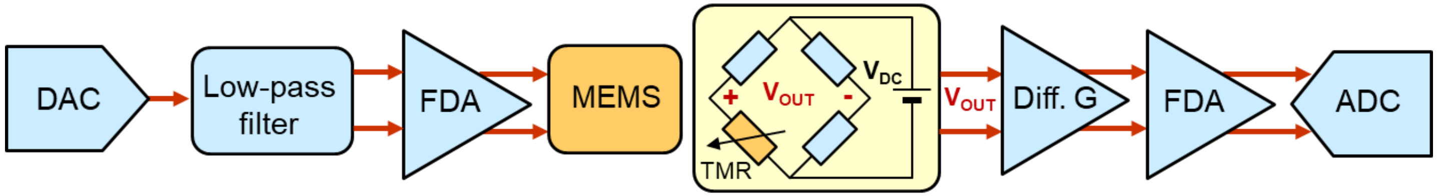

**MEMS modulation at TMR**

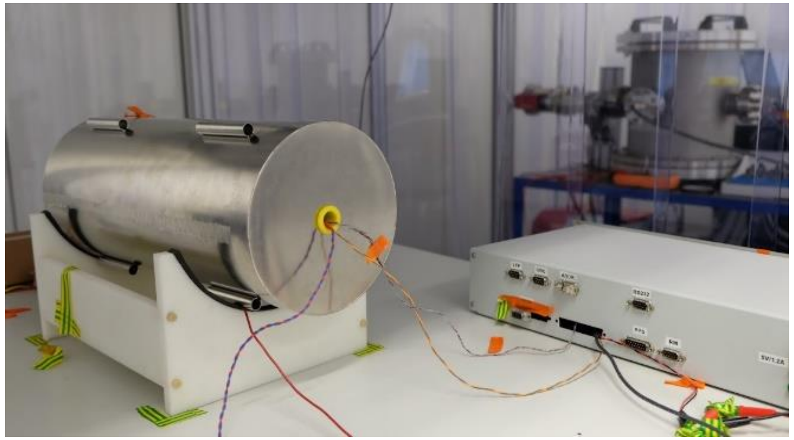
- Modulation depth is measured comparing a test field at 5Hz.
  - Before MEMS assembly (to avoid MEMS insertion losses) at 5 Hz: → 6.16 µT
  - MEMS excited at resonant frequency 1st mode: 276.12 Hz
  - After assembly, at the modulated frequency: 276.12 ± 5 Hz: → 1.22 µT

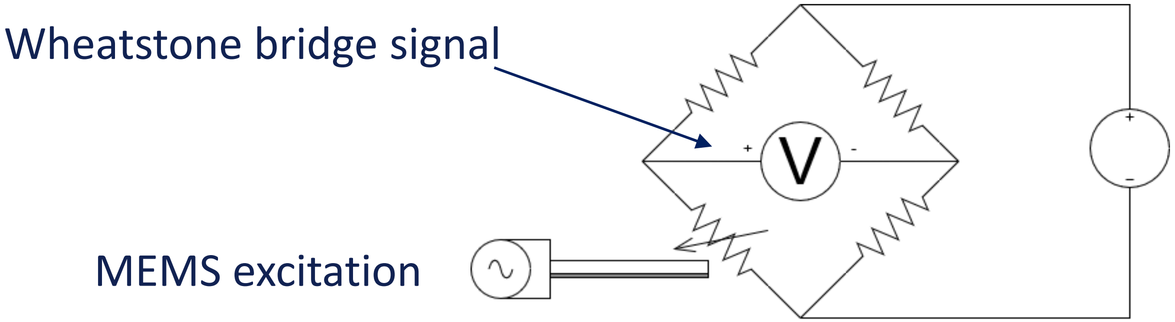
# Final Sensor Form

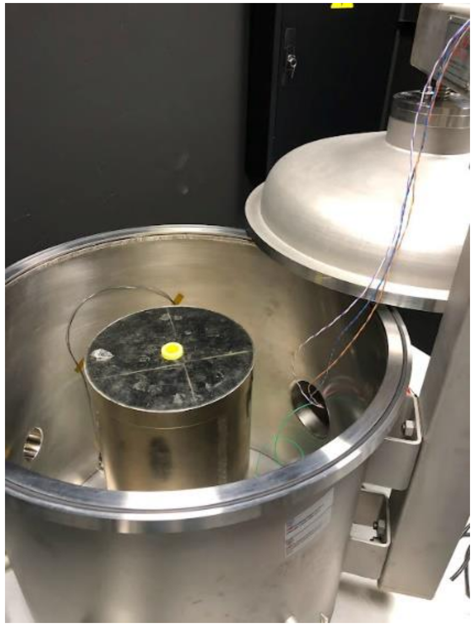


# Electronic acquisition & control



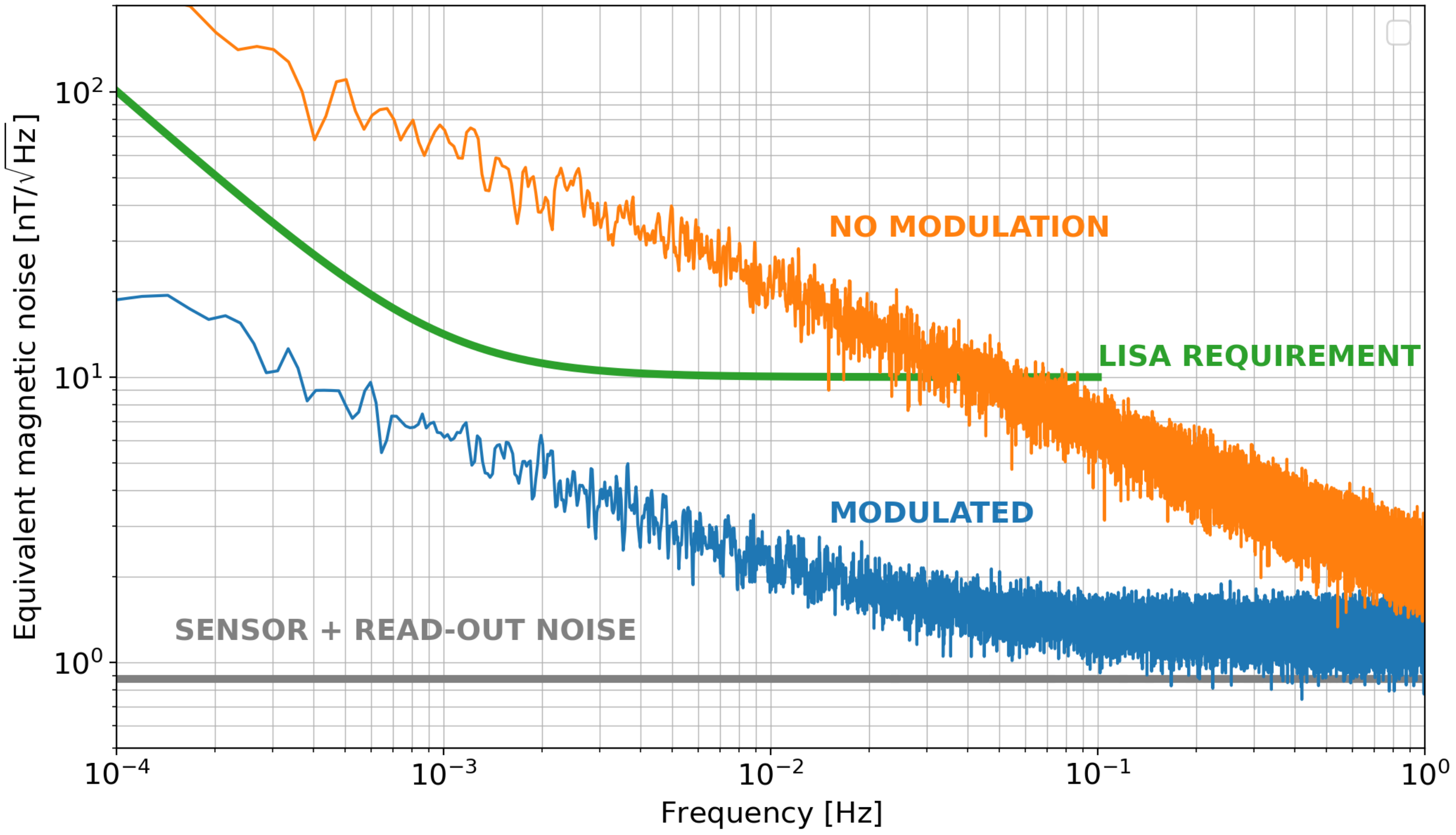





- MEMS must be excited accurately at its resonant frequency.
- Very low-noise electronic acquisition chain.

# System characterization at low pressure




Noise floor reduced by ~ 1 order of magnitude

**Noise floor fulfills the requirements!**

# MELISA project  Conclusions

- Noise objectives have been achieved.

- This proves that magnetic modulation systems on TMR sensors can be useful in space applications.

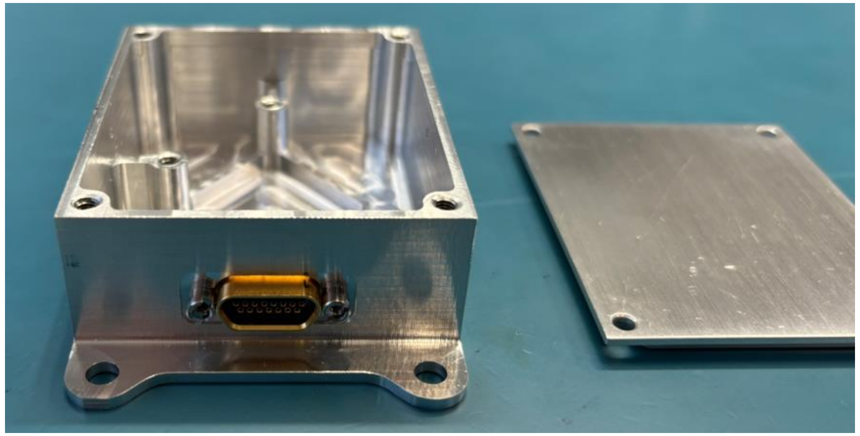
**Next steps, towards ILIADA**

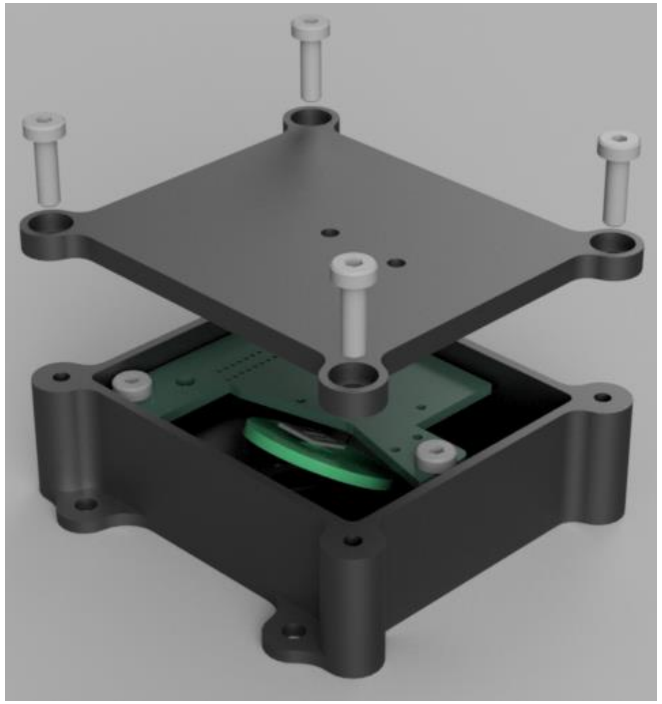
**Paper:**

*X. Manyosa, D. Roma-Dollase, M. Arqué, B. Bonastre, V. Jiménez, J. Ramos-Castro, J. Pons-Nin, V. Martín, J. SalvansTort, S. Gómez, A. Sanuy, J. Mauricio, D. Gascon, M. Nofrarias, M. Domínguez-Pumar. "MEMS miniaturized low-noise magnetic field sensor for the observation of sub-millihertz magnetic fluctuations in space exploration." Measurement 230 (2024): 114489.*

# Towards ILIADA

- A box has been designed to conceal the sensor inside of ILIADA.



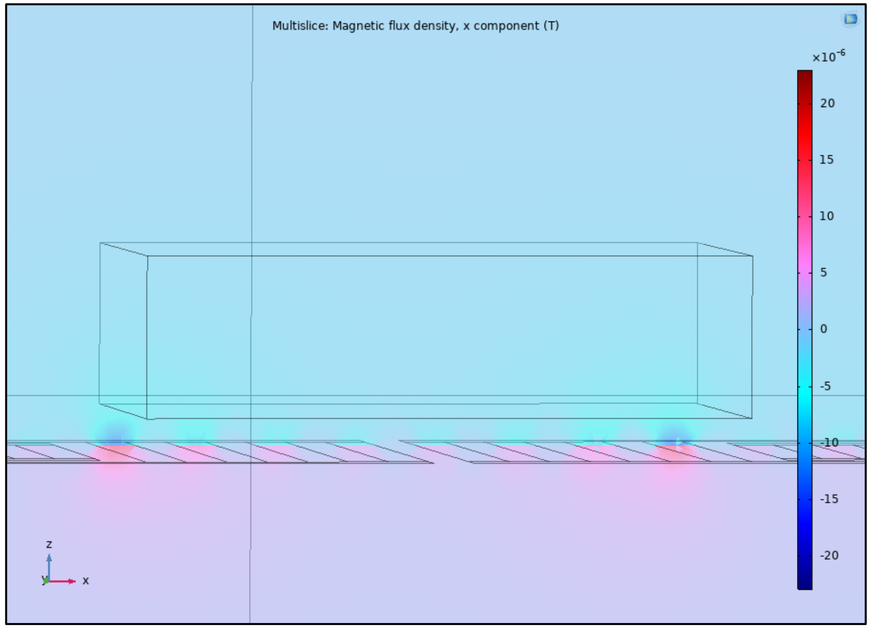


- Main challenge: **Temperature fluctuations**
    - Expected to be of ~40ºC, with a 90 minute period.
    - The **TMR sensitivity** and the **MEMS resonance frequency** have a relevant dependency on temperature.

# TMR sensitivity solutions

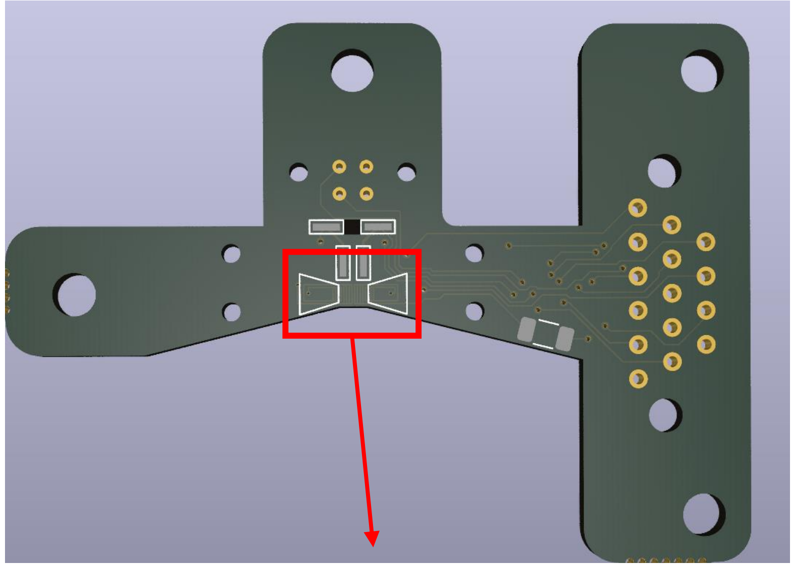
- A concealed coil in the PCB will be used to track the sensitivity of the system.
- On ground calibration of the system will be done.
- The temperature will be monitored using a Pt1000 RTD, to apply a correction if necessary.

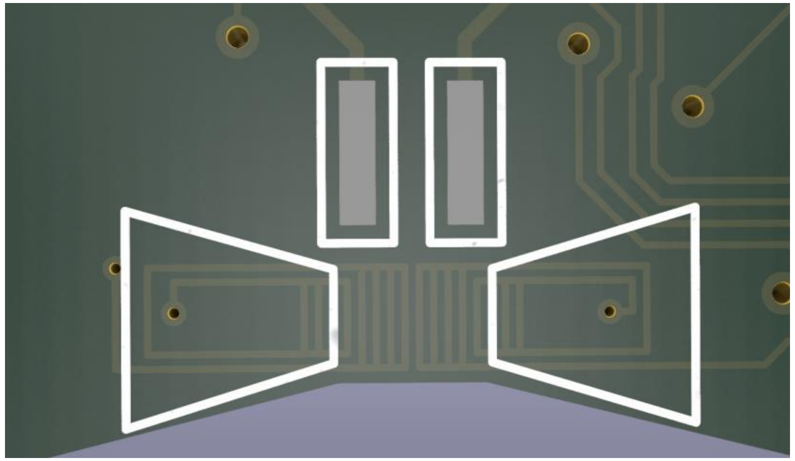
- FEM simulations have shown that with the current design of the coil, magnetic fields of 1.5 $\mu T$ can be achieved with a current of 5 $mA$.




- A significant reduction of the magnetic field at 20mm ($< 1\ nT$)

- Uniform magnetic field at the sensor ($\sigma = 0.1\ \mu T$)

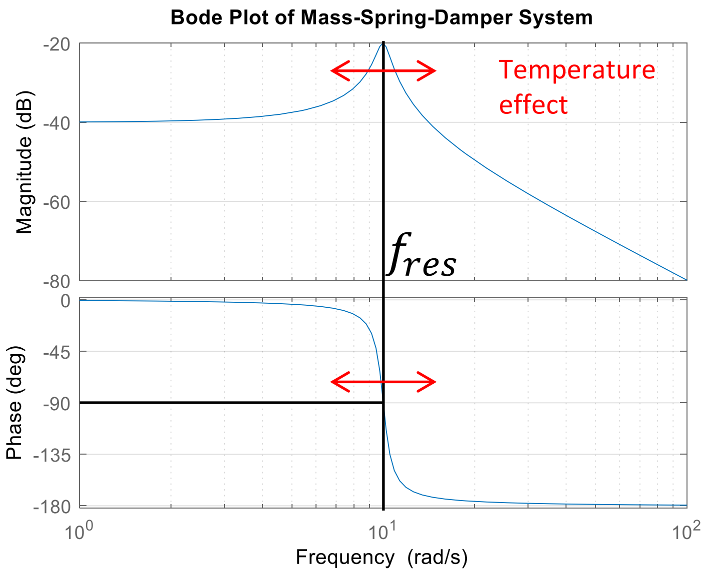


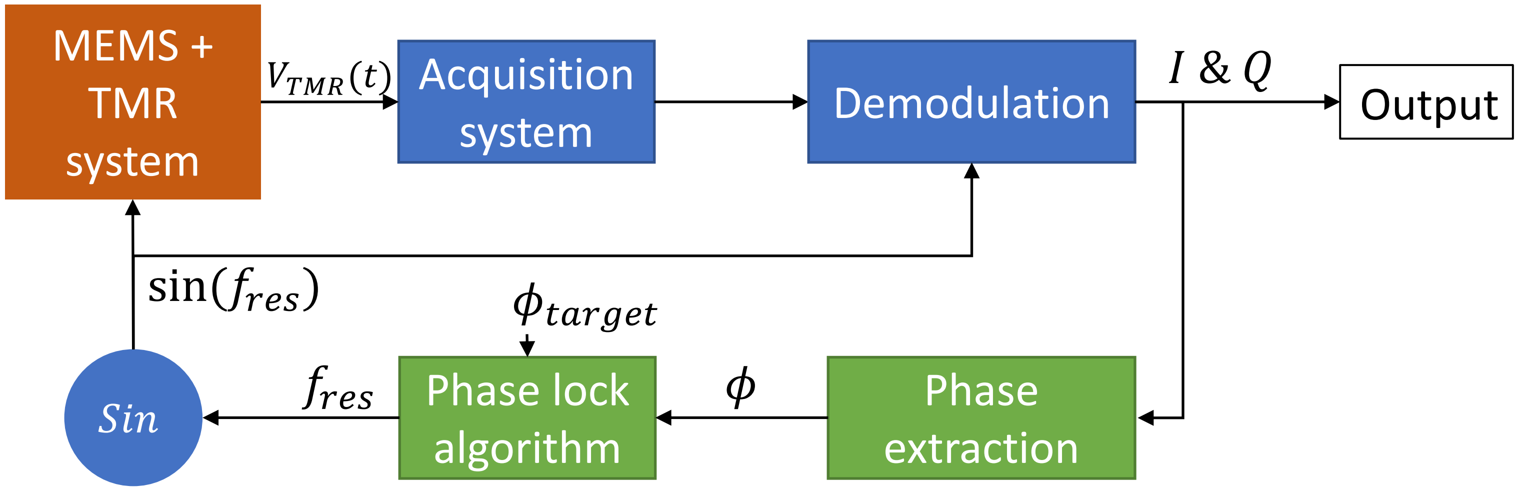


# MEMS resonance frequency solution

- A closed loop system will “follow” the resonance frequency of the system by locking the total phase of the system.

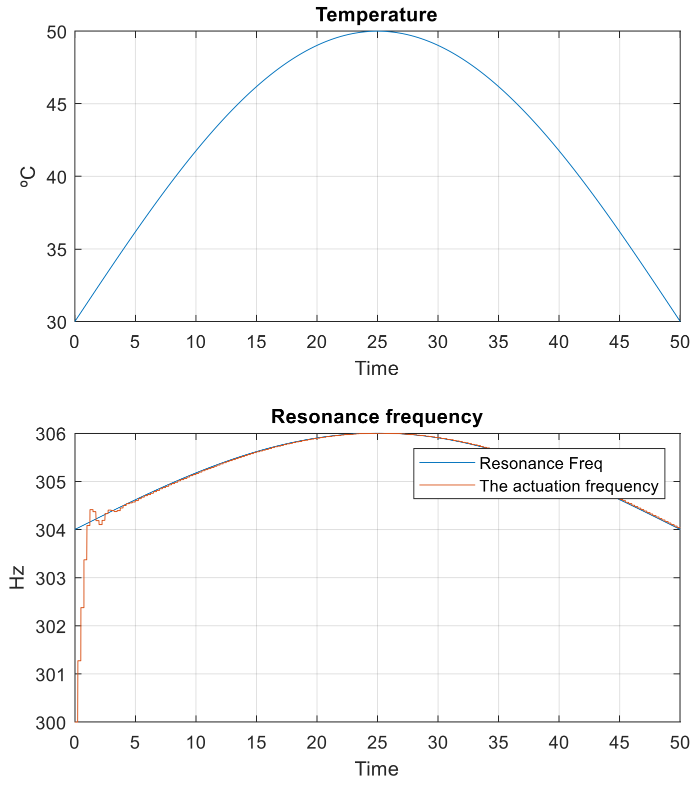
  - With the coil on, a periodic sweep of the frequency of excitation will be performed. To obtain $f_{res}$ and $\phi_{res}$.
  - The $\phi_{res}$ will be locked by the close loop, so the $f_{excitation} = f_{res}$.

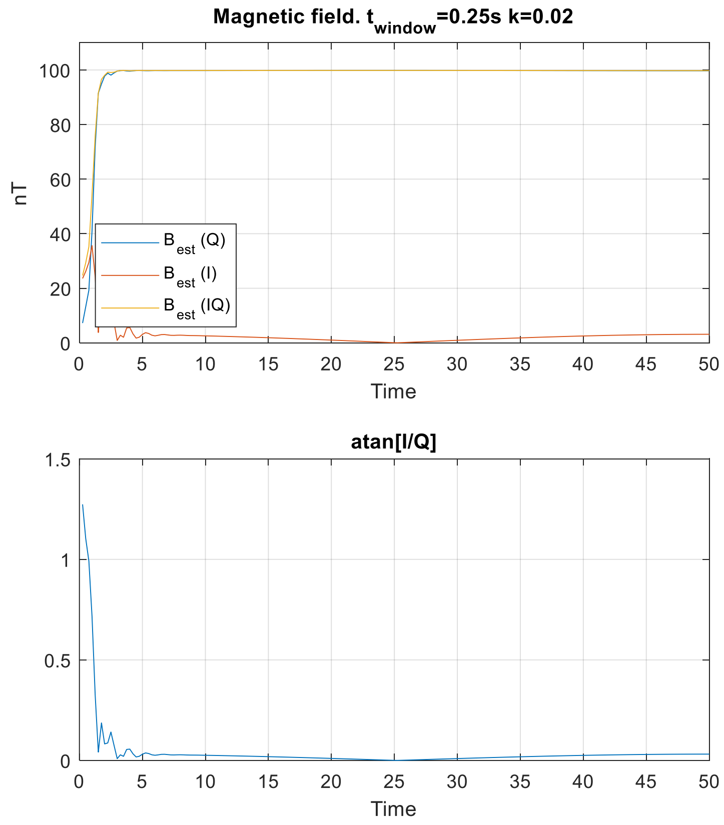


# Preliminary close loop simulations

- Parameters:
  - Using mass-spring dynamics
  - 100 nT AC magnetic field
  - 0.1 Hz/K Temperature dependance
- The system is able to “follow” the resonance frequency, and to obtain a good magnetic field estimation.



# Next steps towards ILIADA

- Mount the system with the new PCBs
- Test the close loop control
- Characterize the temperature dependency of the whole system
- Obtain space qualification (outgassing, TVAC…)

Thank you!