MSC Seminar

Electron spin resonance magnetic field sensors for the B-Train systems

A. Beaumont[1], G. Boero[2], M. Buzio[1], D. Giloteaux[1], A. Matheoud[2]

[1]CERN, [2]EPFL

Outline

- ➔ **Introduction**
- ➔ **Design**
- ➔ **Results and experimental validation**
- ➔ **Conclusions and future perspectives**

Introduction: B-Train (1/2)

➔ **Real-time magnetic field measurements:**

<u>Purpose</u>:

- **Measure the field of the main bending magnets**

of the Synchrotron accelerators

- ⇒ **For the RF accelerating cavities**
- ⇒ **For beam intensity calculation**
- ⇒ **For the power converter of the main bending magnets**

<u>Why</u> measurement instead of simulation?

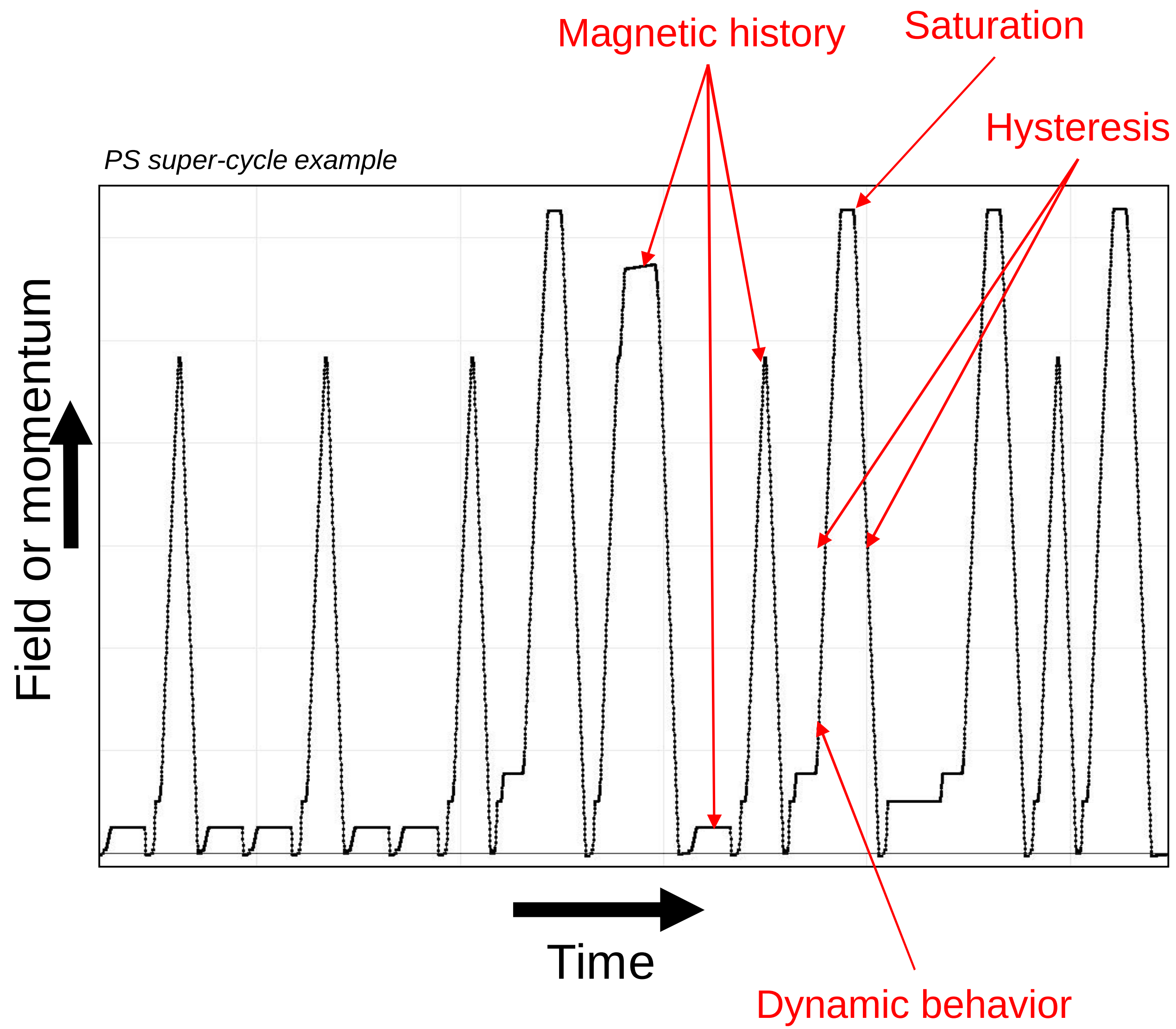
Problem to predict the combined effects

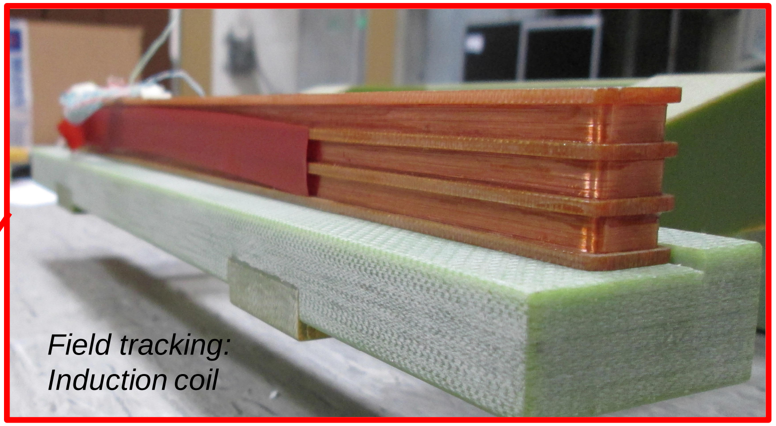
<u>Improvement</u> on the accelerator operation:

- **Increase the field reproducibility**
- **Reduce the cycle time**

<u>What</u> is needed:

- **Absolute local/integral field at 250 kHz**
- **Wide dynamic range from about 0 to 2 T**
- **A reference magnet (when available)**

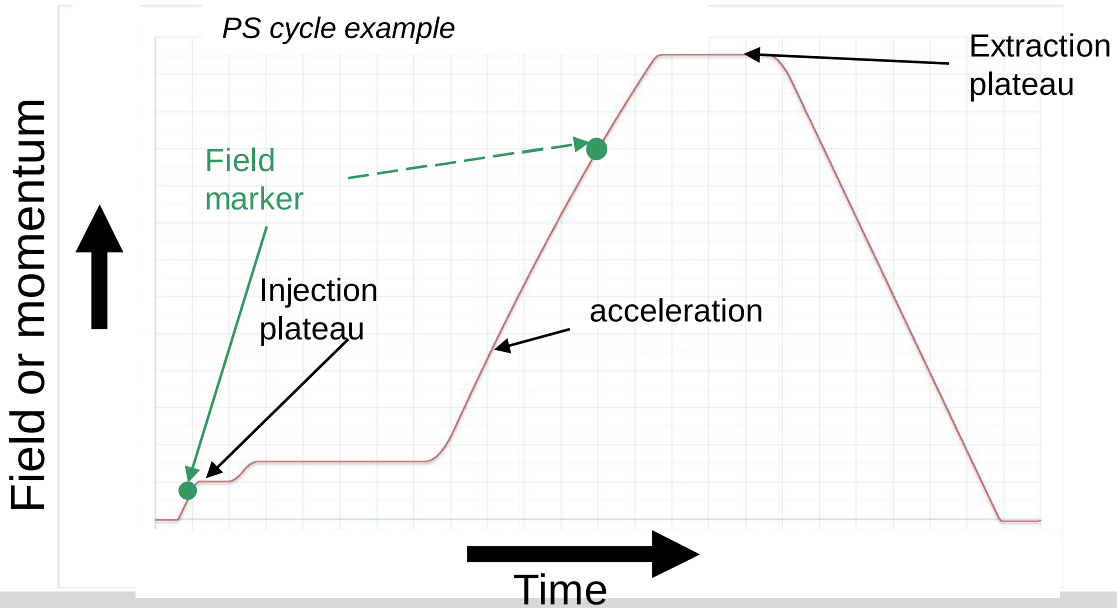




$$B(t) = B_{marker}(t_0) + \frac{1}{A_{coil}} \int_{t_0}^{t} V_{coil}\,dt$$

The reference field — *The field variation*

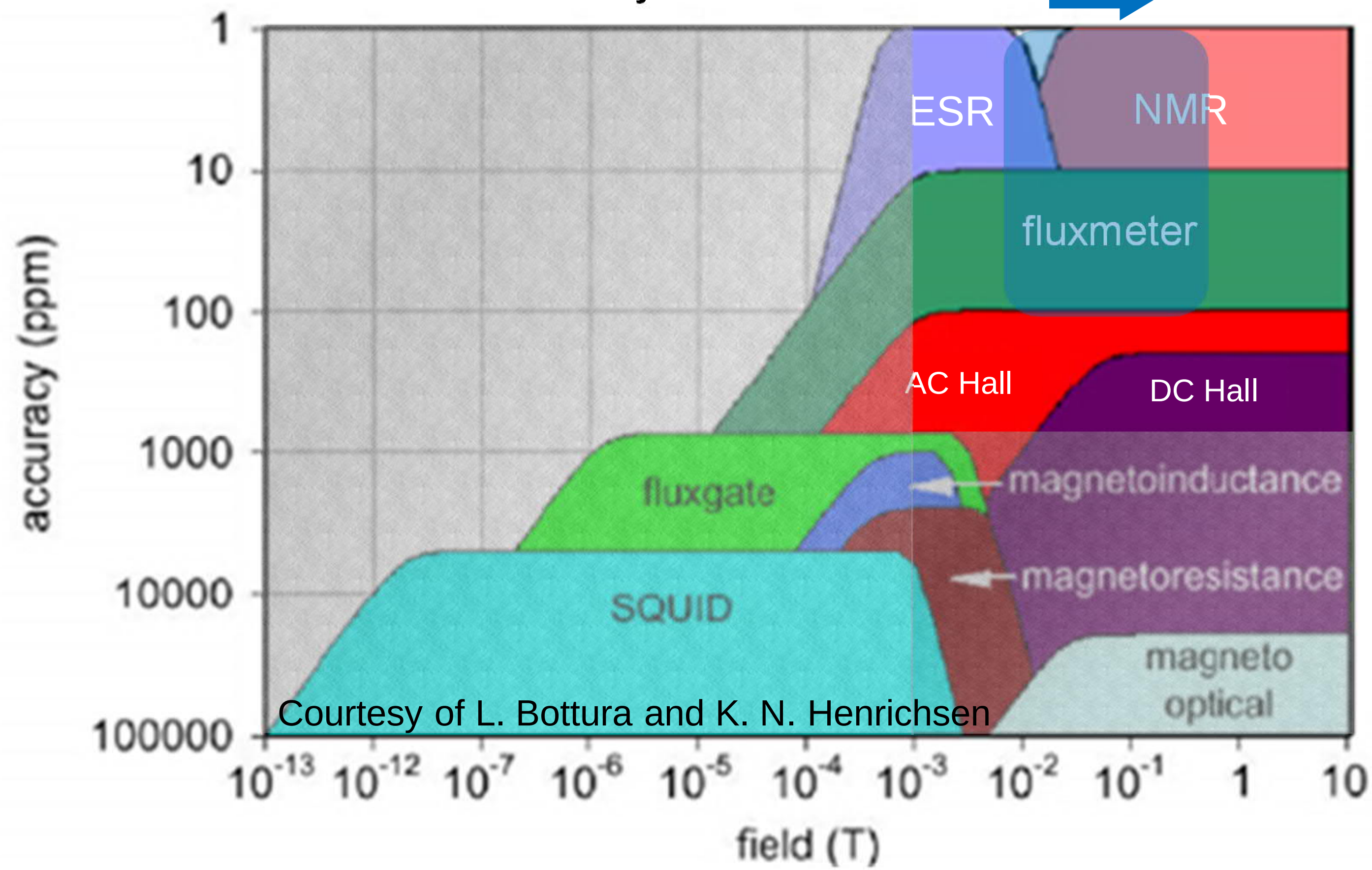
The magnetic field B in (T)
The reference field B_{marker} in (T)
The starting time t_0 in (s)
The coil surface A_{coil} in (m^2)
The induced coil voltage V_{coil} in (V)



Introduction: Marker sensors (1/2)

➔ **Minimum requirements:**

- **Field range: up to 0.7 T**
- **Field ramp rate: up to 5 T/s**
- **Field gradient: up to 1.2 T/m, equivalent to an inhomogeneity G/B_{marker} of 10 m^{-1}**
- **Field reproducibility : better than 10^{-4} at beam injection**
- **Reliability: only few hours of downtime per year allowed**
- **Required lifetime: > 20 years**
- **Field absolute accuracy: 10^{-3}**



Hall probes [1]:
- Wide dynamic range
- Low stability
- Regular calibration needed

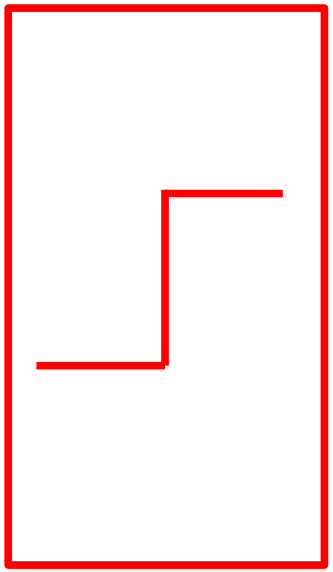
Fluxmeter (rotating or translating):
- Not real time

NMR (Nuclear Magnetic Resonance) [2]:
- Metrological reference
- Field inhomogeneity < 0.06 m^{-1}
- Low field ramp rate <0.1 T/s

ESR (Electron Spin Resonance) [3,4]:
- High inhomogeneity field > 5 m^{-1}
- High field ramp rate > 2.3 T/s
- **Calibration and operation**
- **Low field measurement < 10 mT**

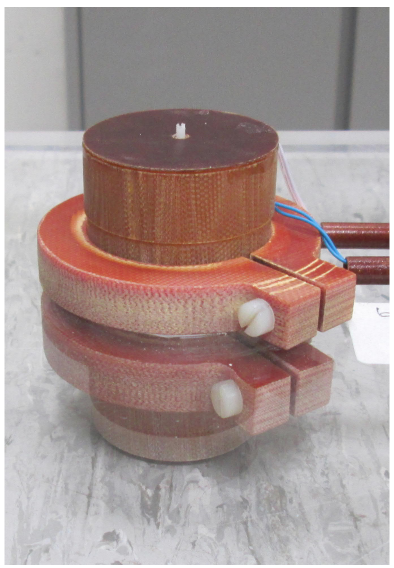
➔ Markers used in the CERN accelerators

Software Marker



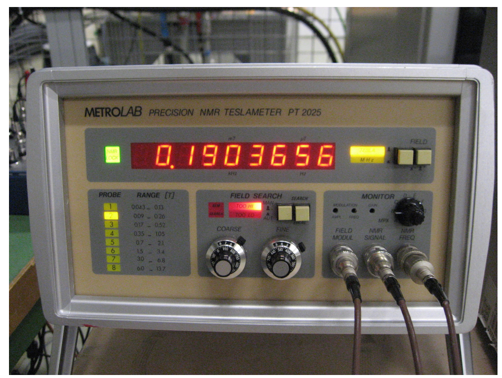
Preset value

Peaking Strip



5 mT

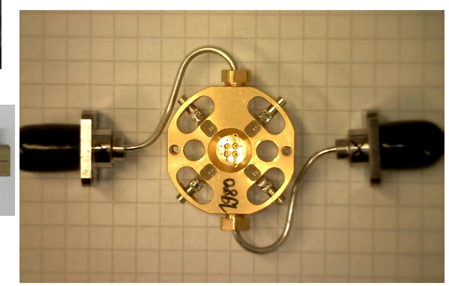
NMR



~43-2000 mT

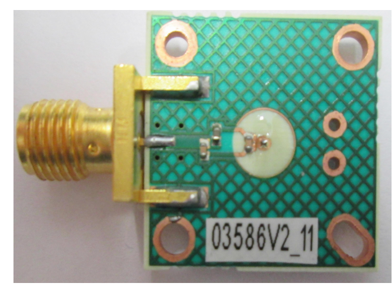
ESR

Ferrimagnetic resonance (FMR)



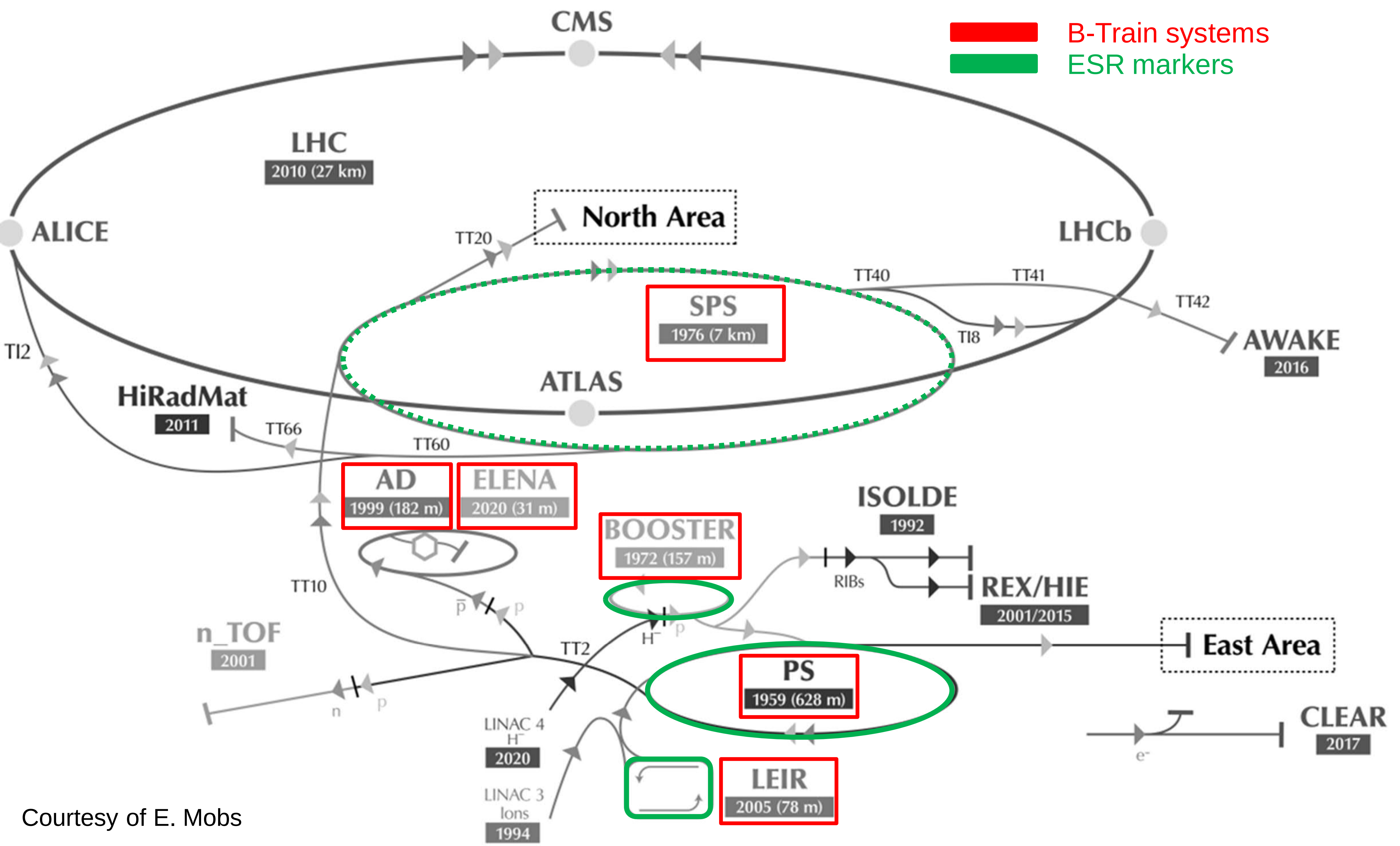
~36-50 mT

Electron paramagnetic resonance (EPR)



~36-760 mT

Introduction: ESR sensors at CERN



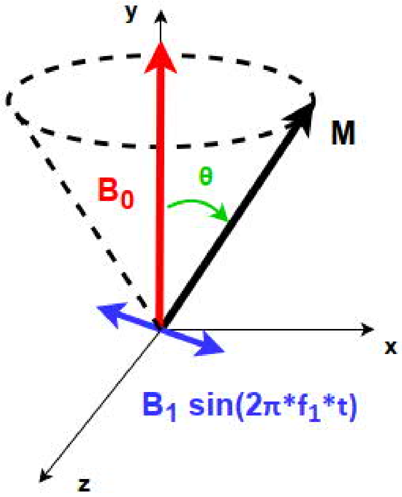
Courtesy of E. Mobs

➔ **Magnetic resonance:**

- In presence of a background magnetic field B_0

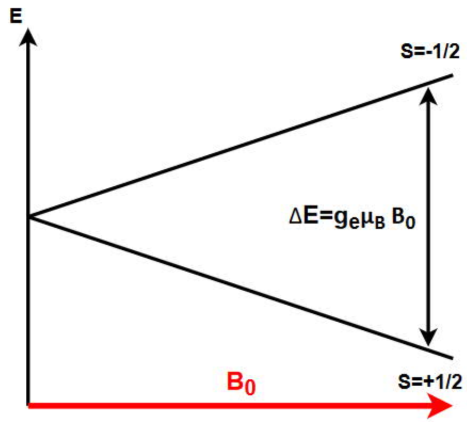
Classical view

$$\frac{1}{\gamma_e}\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \mathbf{B}_0$$



Quantum view

$$\Delta E = hf_0$$



- When sample is irradiated with an external microwave $B_1 \perp B_0$
- The resonance occurs when $f_1 = f_0$:

The Larmor frequency is given by

$$f_0 = \frac{\gamma}{2\pi} B_0$$

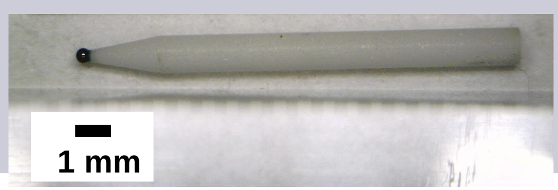
$\frac{\gamma_{n(^1H)}}{2\pi}$ = 42.6 MHz/T (for proton)

$\frac{\gamma_e}{2\pi}$= 28025 MHz/T (for an isolated electron)

Factor ~670 !

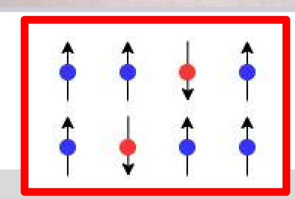
These two gyromagnetic ratios are known within 10^{-7} accuracy or better [5]

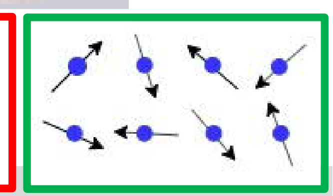
Introduction: Magnetic resonance material

	FMR	EPR
Magnetic property	Ferrimagnetic[1]	Paramagnetic[2]
Material	Gallium doped Yttrium iron garnet (GaYIG)	Organic free radical α,γ-bisdiphenylene-β-phenylallyl (BDPA)
Chemical composition	$GaY_3Fe_5O_{12}$	$C_{39}H_5$
Usage	Microwave applications	Standard for EPR spectrometers
Spectrum	Single narrow linewidth	
Minimum operating field	30 mT (with Gallium doping)	$< 1\ \mu T$
Anisotropy	high	very low
Signal amplitude (same detection electronic)	1500 mV	15 mV
Commercial presentation		

[1]:Two unequal populations of atoms with anti-parallel magnetic moments and magnetization ≠ 0

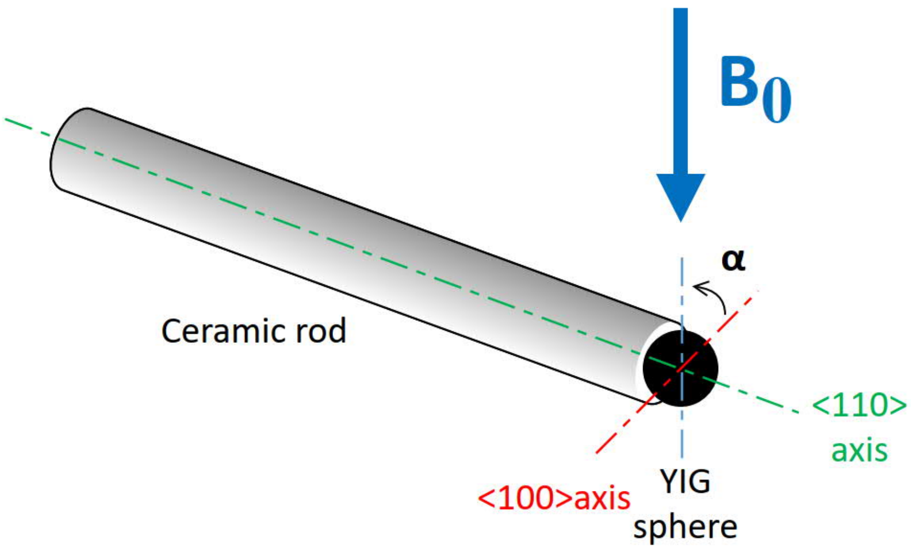
[2]:B=0 T magnetic moment ≠ 0 but spin randomly oriented (magnetization=0)



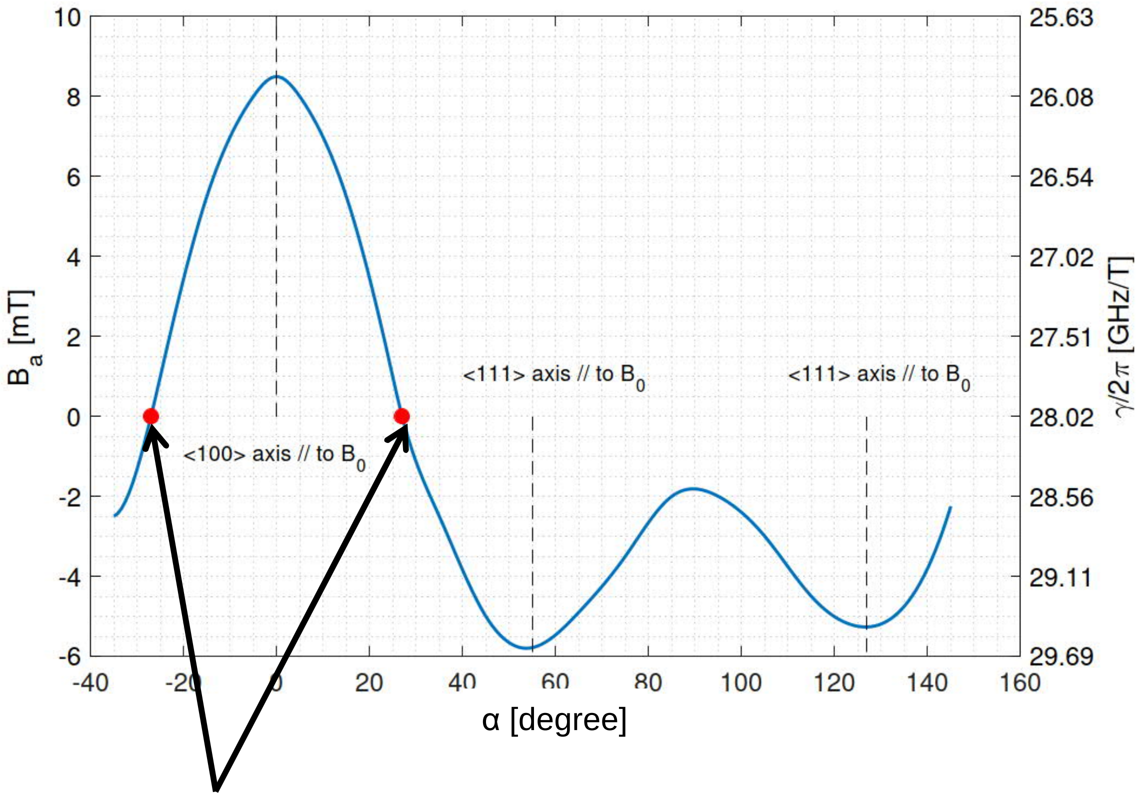


$$f_0 = \frac{\gamma_e}{2\pi}(B_0 + B_a)$$

➔ **B_a depends on crystal <u>axis alignment</u> with respect to B_0 and on the <u>temperature</u>**



$$B_a = B_a'(\alpha)\, B_a''(T)$$



B_a=0 T therefore $\gamma = \gamma_e$, in addition
<u>no more temperature dependency</u>

=> Temperature stable axis at about α= ± 30º

Microwave structures

Broadband devices

- ➔ Transmission line
- ➔ Coupling: typically YIG filter
  - – The magnetic resonance changes the coupling coefficient

Narrowband devices (Optimized for the marker field level)

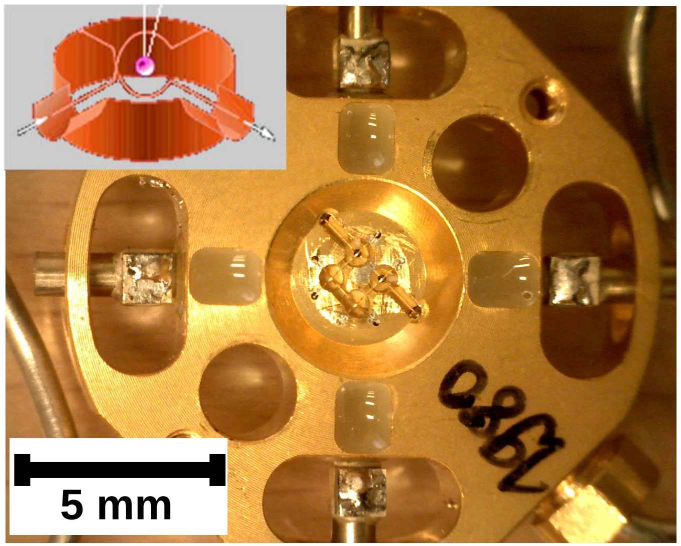
- ➔ Resonator :
  - – RF source provided by external generator
- ➔ Oscillator:
  - – RF source provided by internal generator (cross-coupled transistor)

Magnetic resonance signal detection

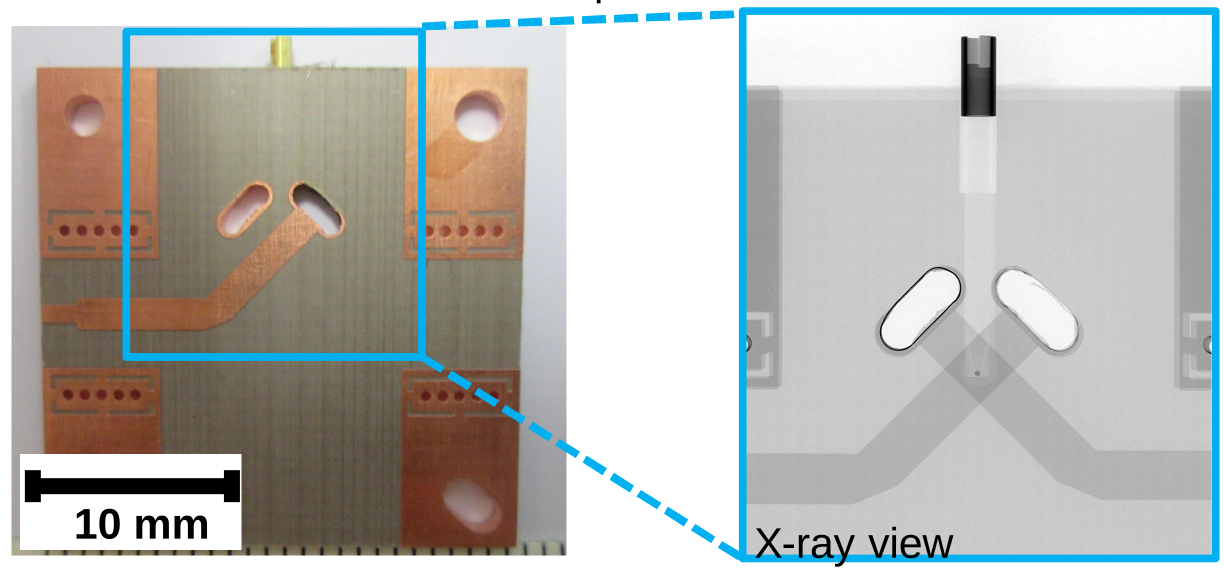
- ➔ Amplitude
- ➔ Frequency
- ➔ Phase

Design: Broadband devices

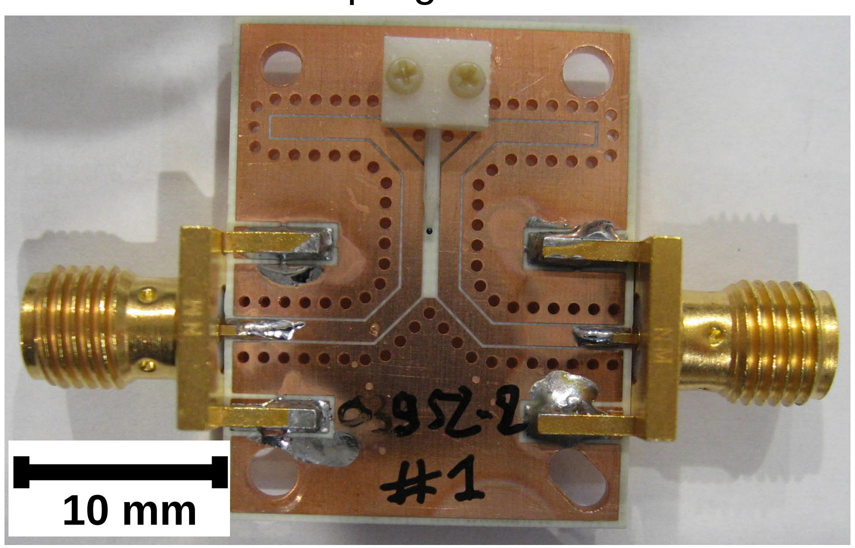
Commercial YIG filter



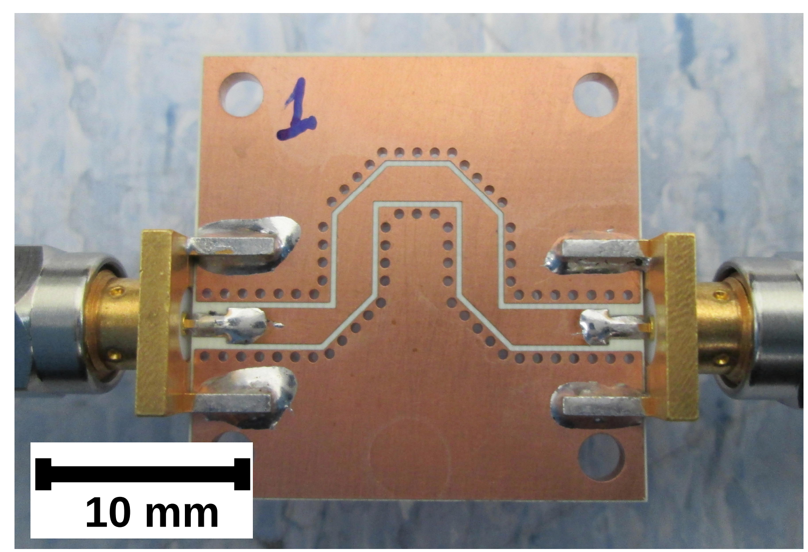
Stripline YIG filter



Coupling structure



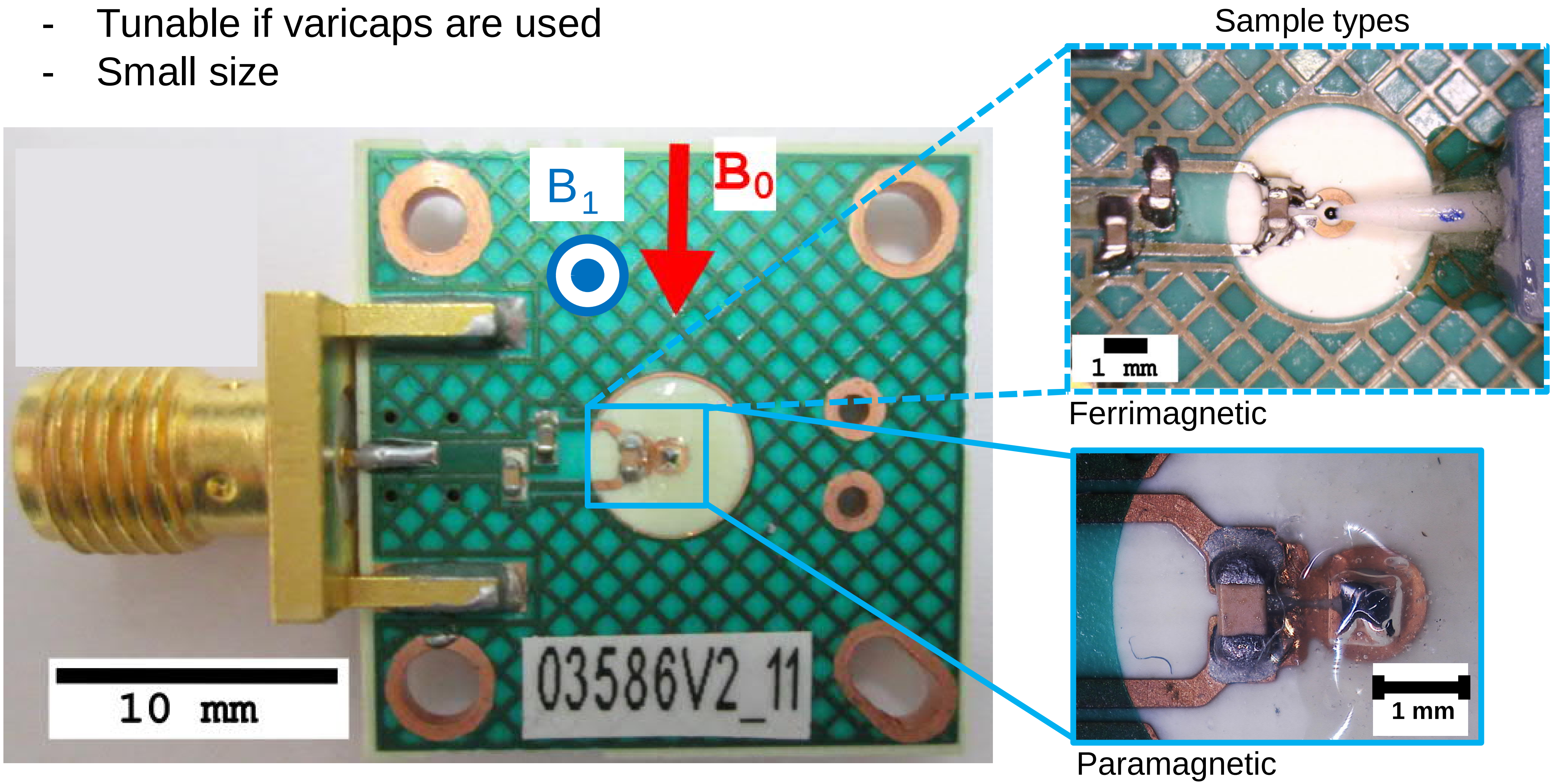
Transmission line

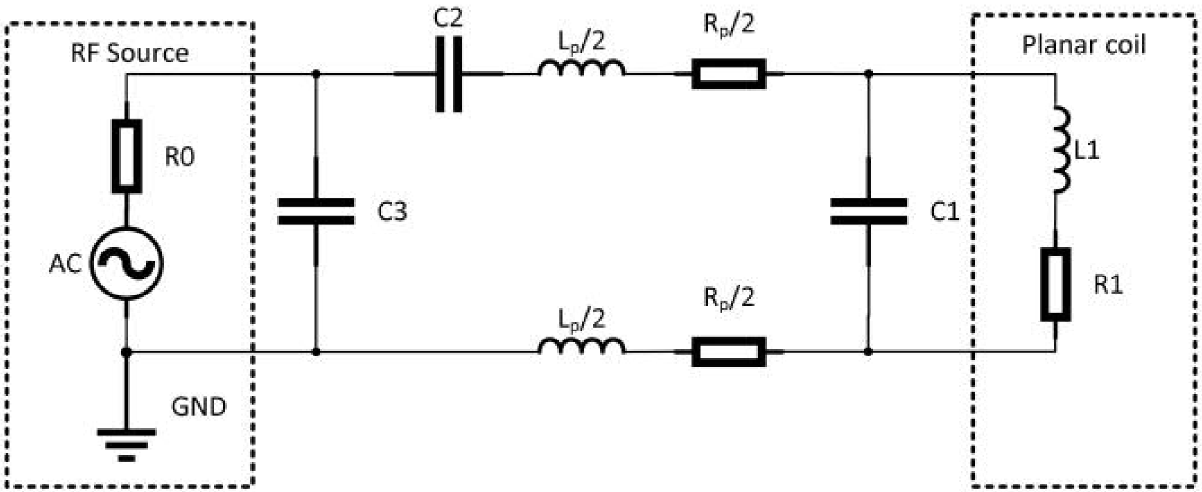


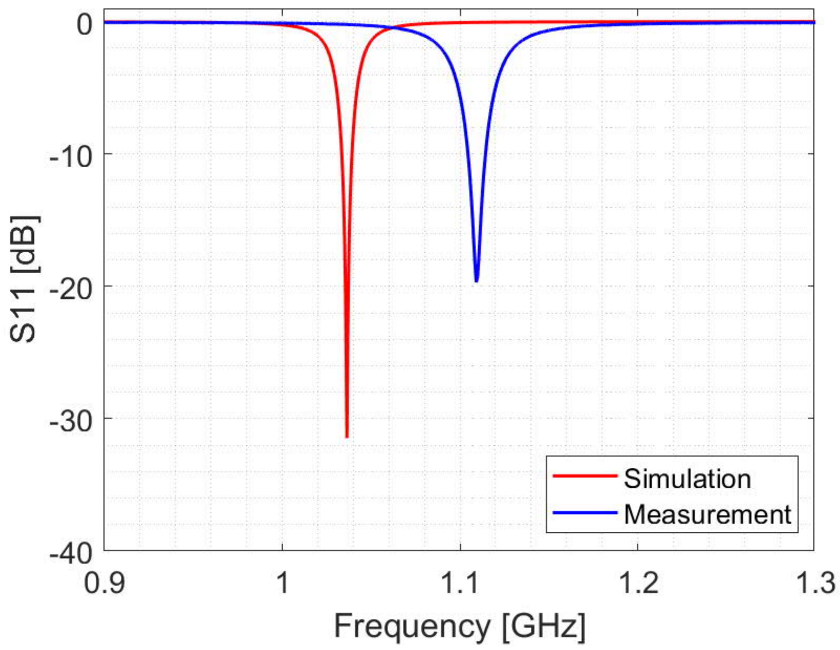
f_0=1 GHz B_0=36 mT

➔ Main application: PS low field marker

- Suitable for RF ≤ 1 GHz
- Non-ferromagnetic elements
- Tunable if varicaps are used
- Small size





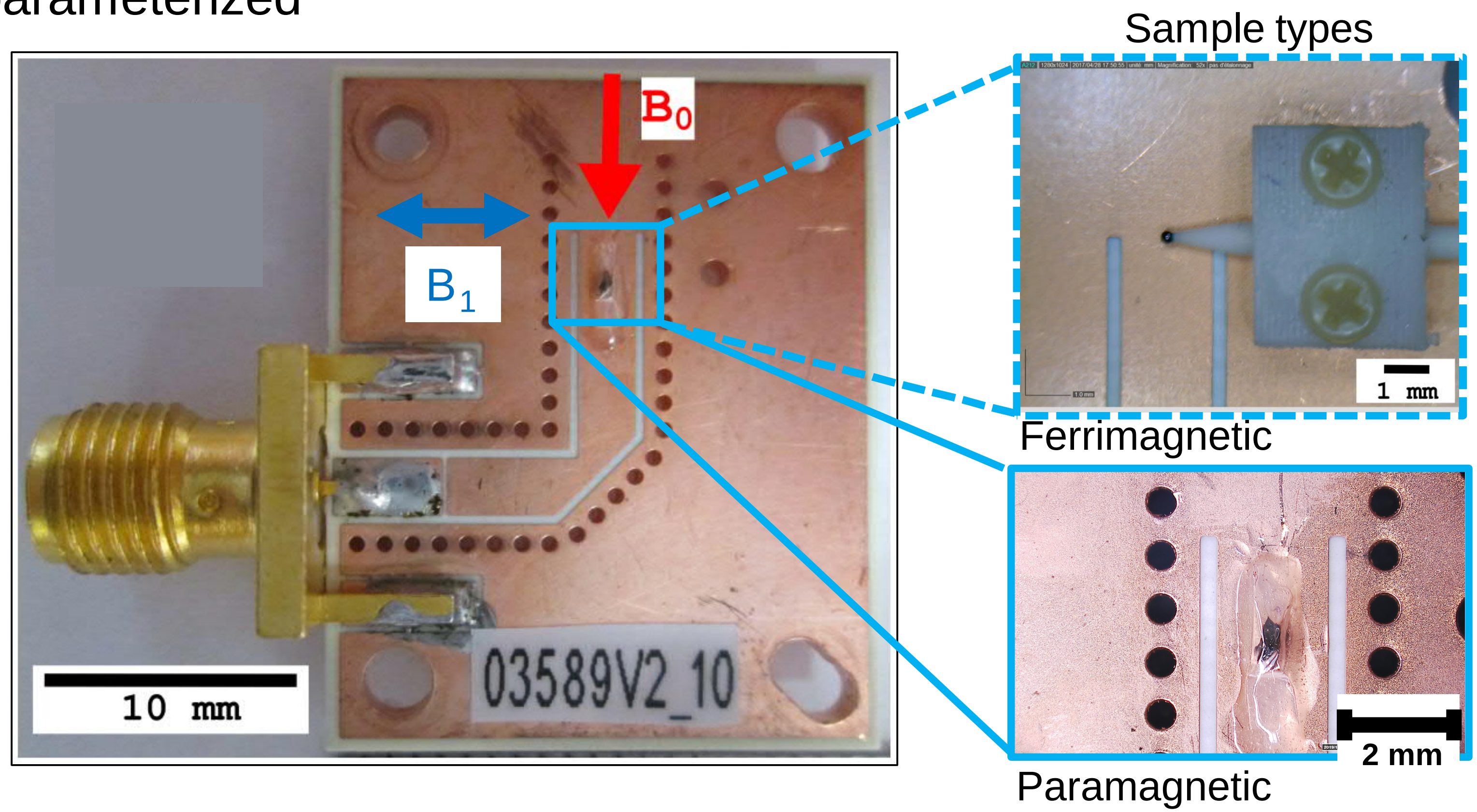


Elements	value
Substrate type	Rogers RO4350 B
Substrate size	20x20x1.5 mm^3
Tuning circuit C1	4.7 pF
Matching circuit C2	4.7 pF
Matching circuit C3	15 pF
L1	1.2 nH
R1 at 1 GHz	38 mΩ
L_p	4.13 nH
R_p	1.35 Ω
f_{res}	1.109 GHz
S_{11}	-19 dB
Q-factor at -3 dB	36

Grounded CoPlanar Waveguide f_0=3 GHz B_0=106 mT

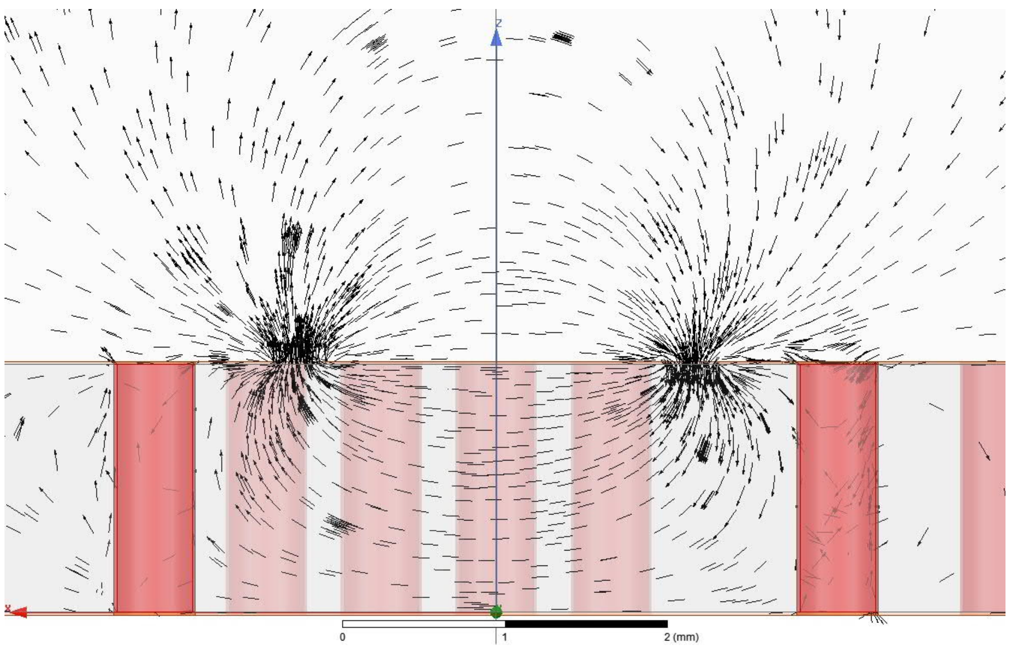
➔ **Main application: LEIR&PSB low field marker**

- Suitable for RF > 1 GHz
- Small size when using $\lambda/4$
- Better control of the resonance frequency
- Fully parameterized

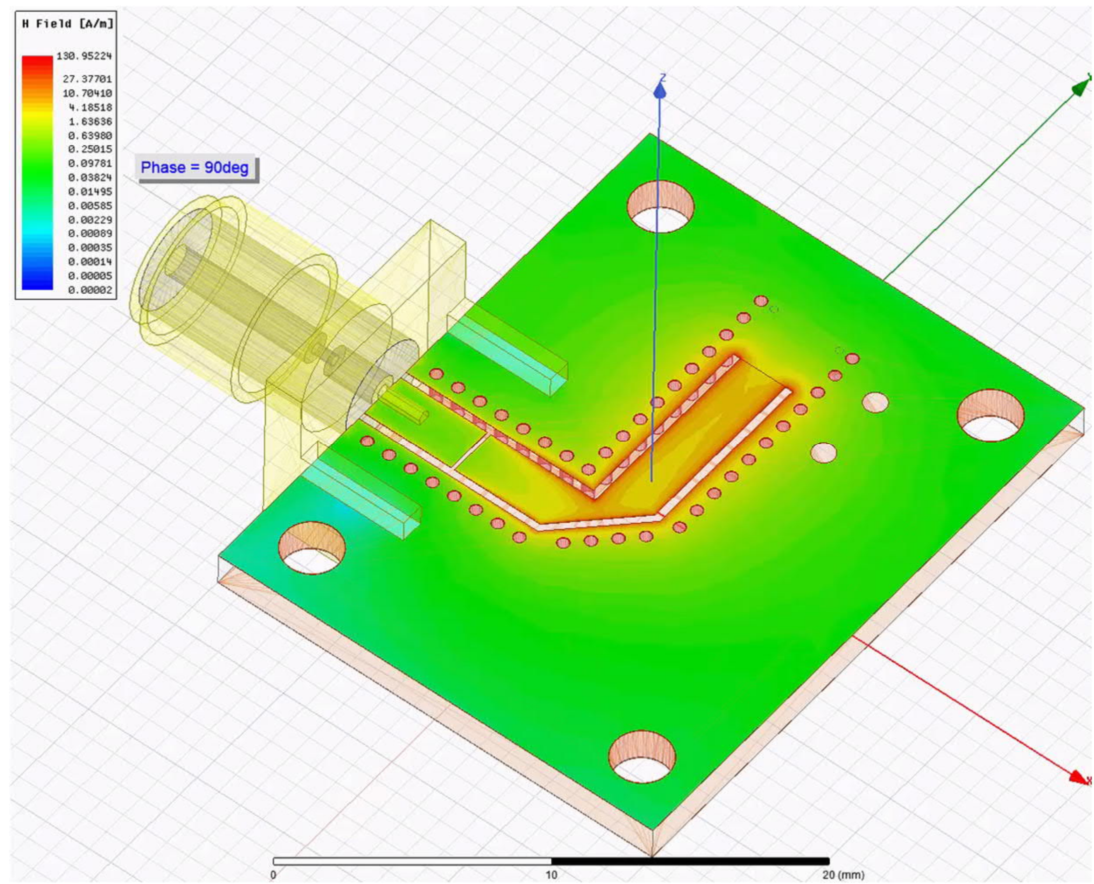


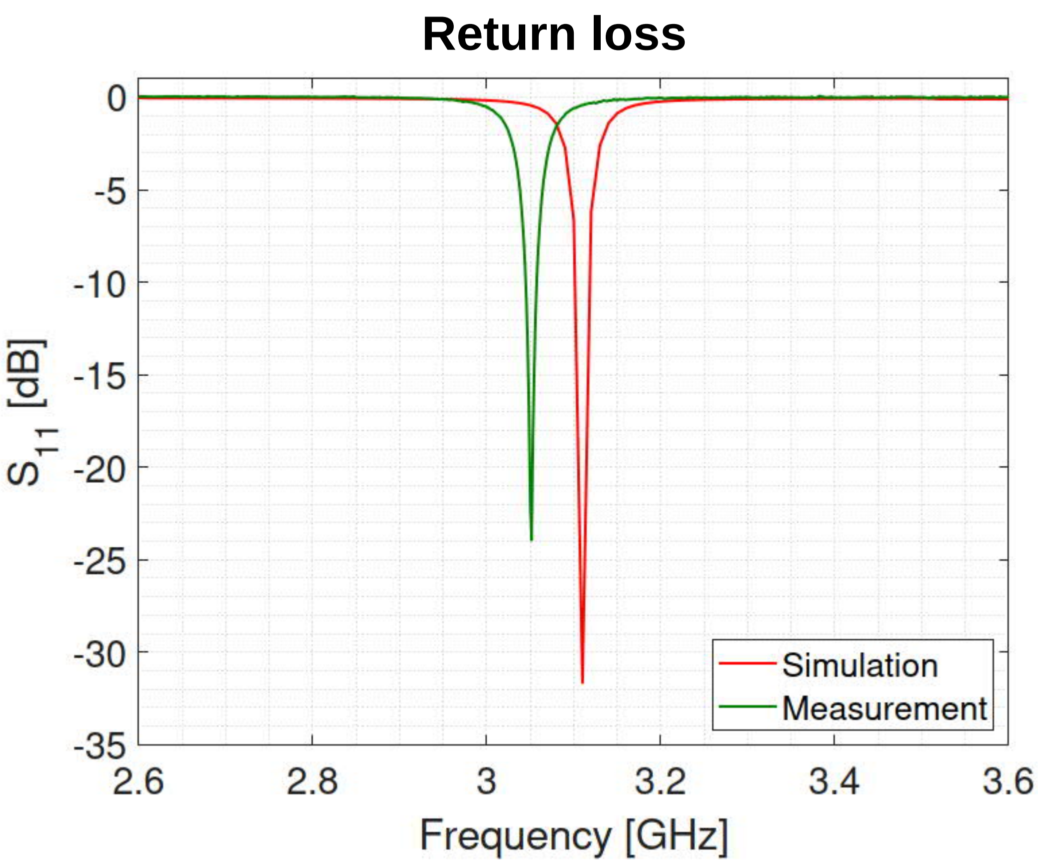
➔ **HFSS (Ansys Electronics Desktop) 3D simulation**

Magnetic field lines distr.



Magnetic field strength

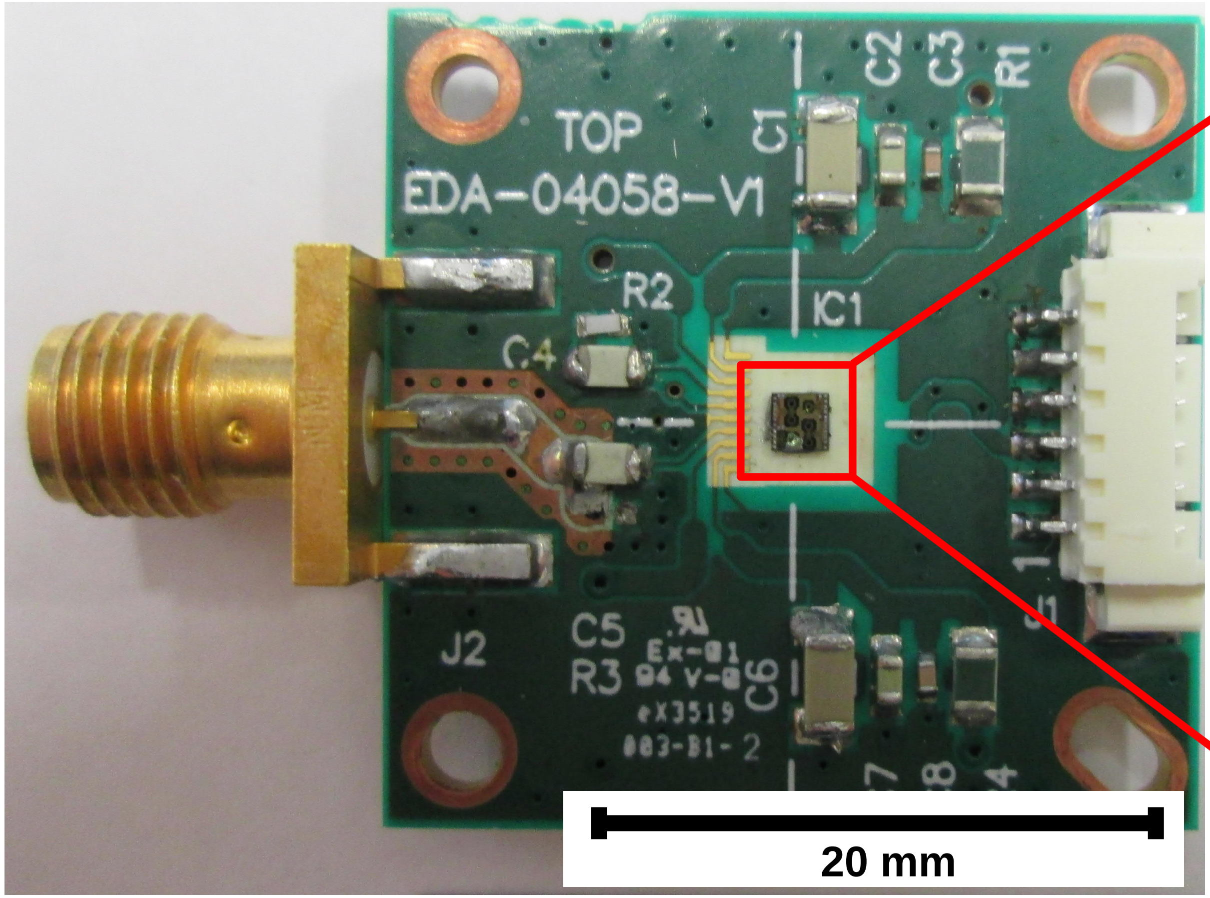


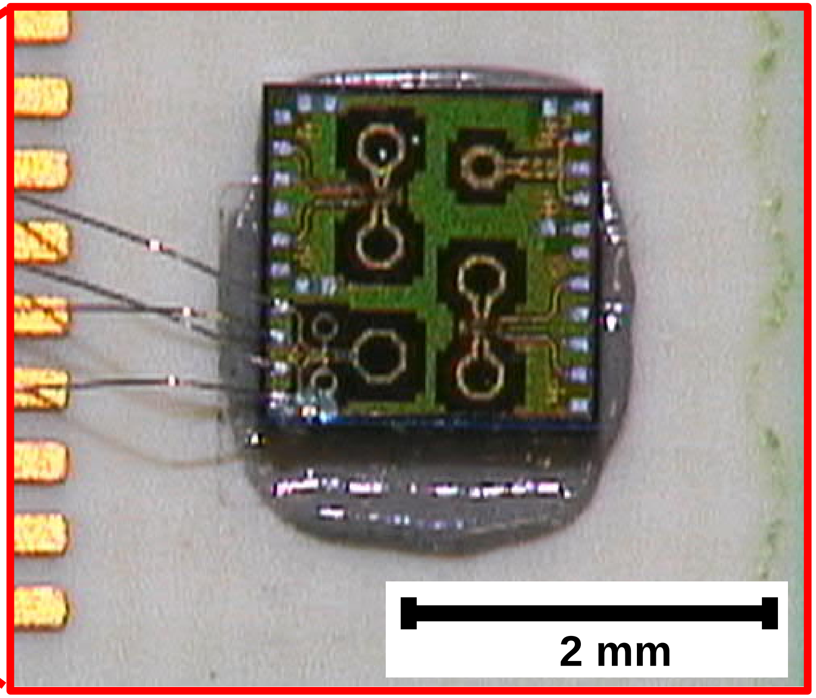


Elements	value
Substrate type	Rogers RO4350 B
Substrate size	25x20x1.5 mm^3
Strip width	2.1 mm
Strip length	15.25 mm
f_{res}	3050 GHz
S_{11}	-24 dB
Q-factor at -3 dB	70

Integrated oscillators chip

Designed at EPFL by Dr. G. Boero and Dr. A. V. Matheoud

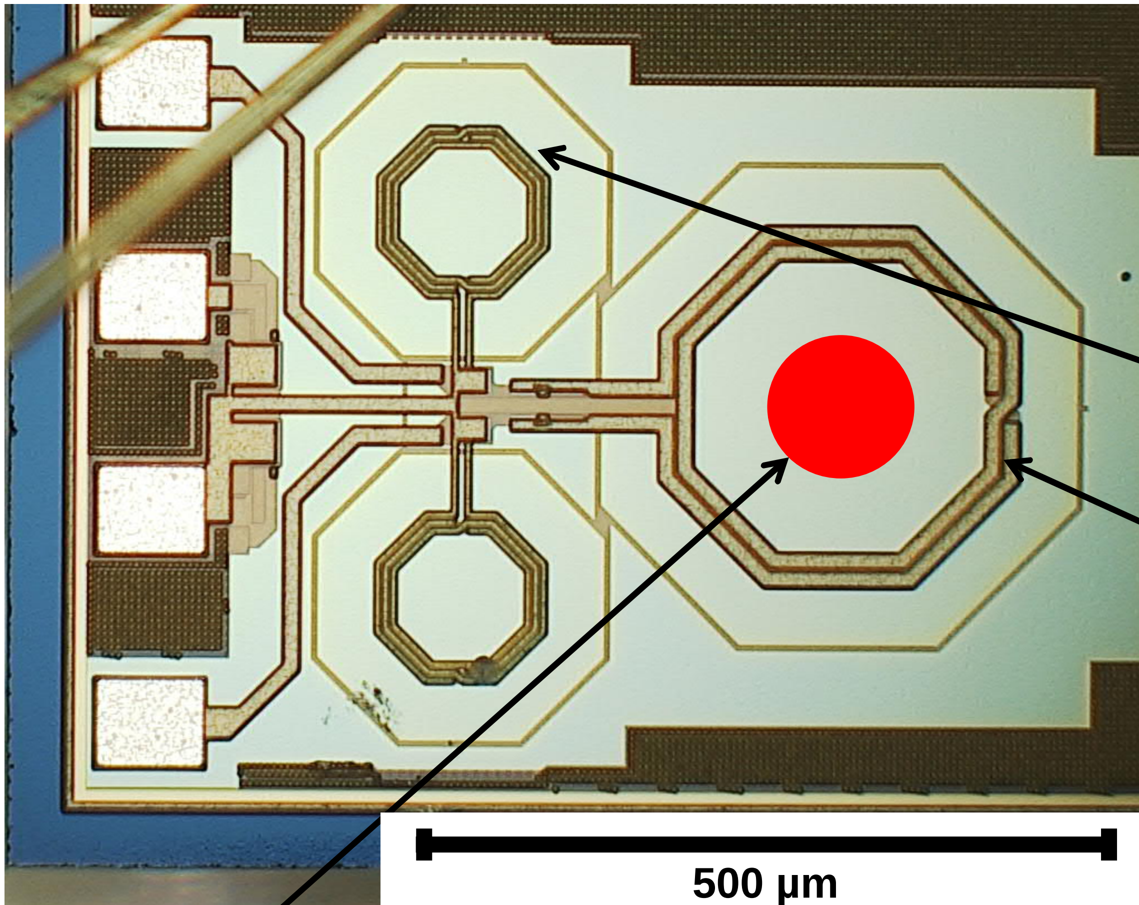




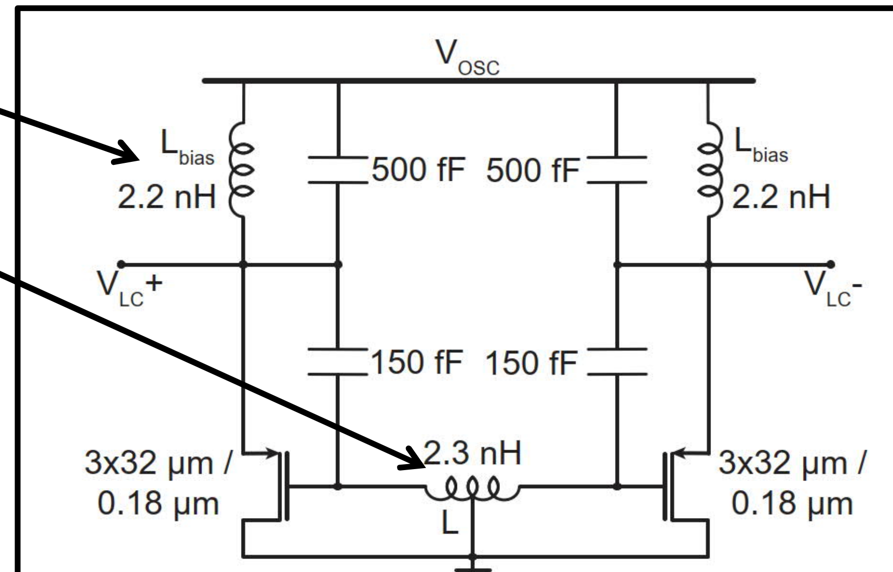
Design: Oscillators (2/5)

Used of Integrated oscillator f_0=10 GHz B_0=360 mT [6]

- Cross-coupled LC oscillator
- Manufactured in CMOS integrated circuit technology
- Fixed frequency

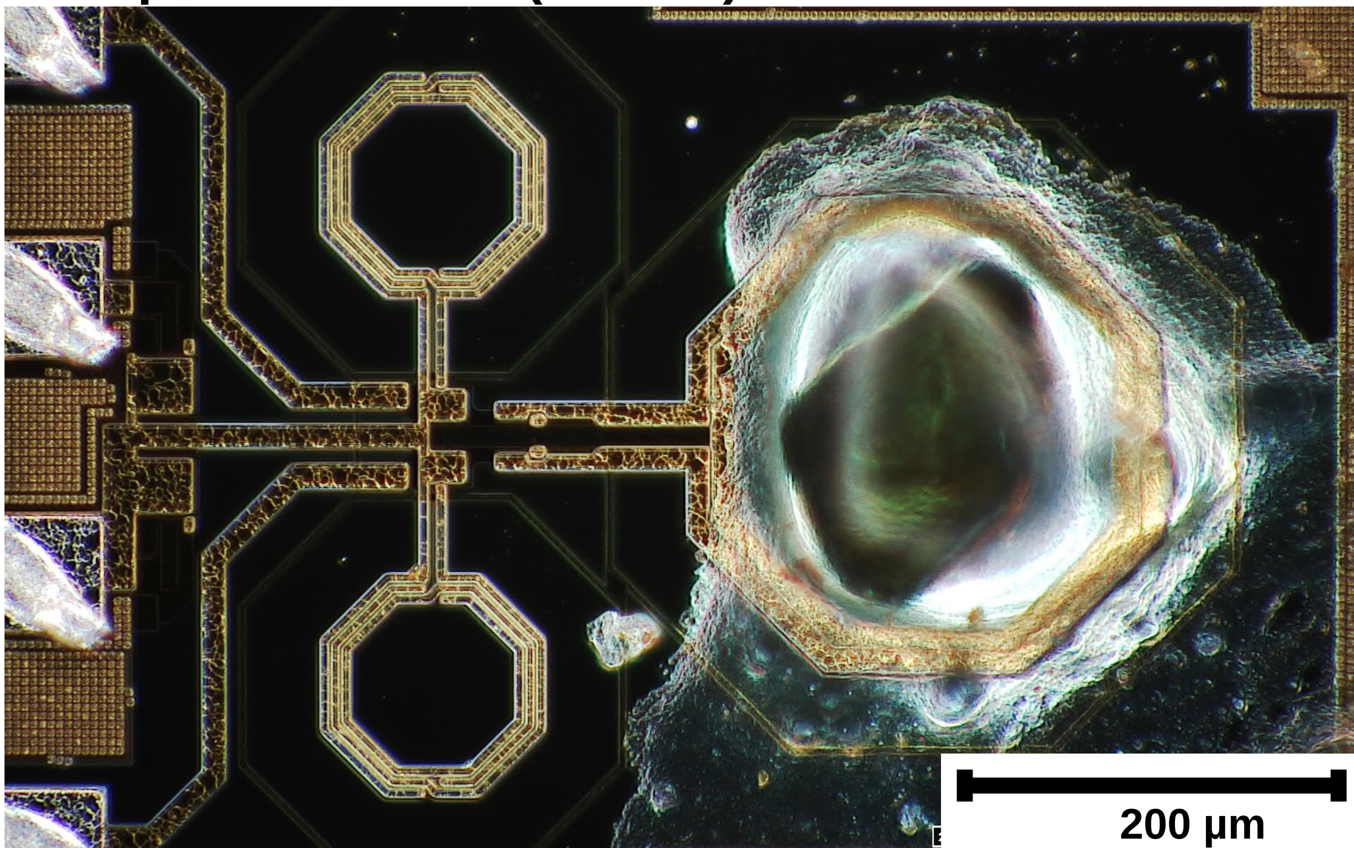


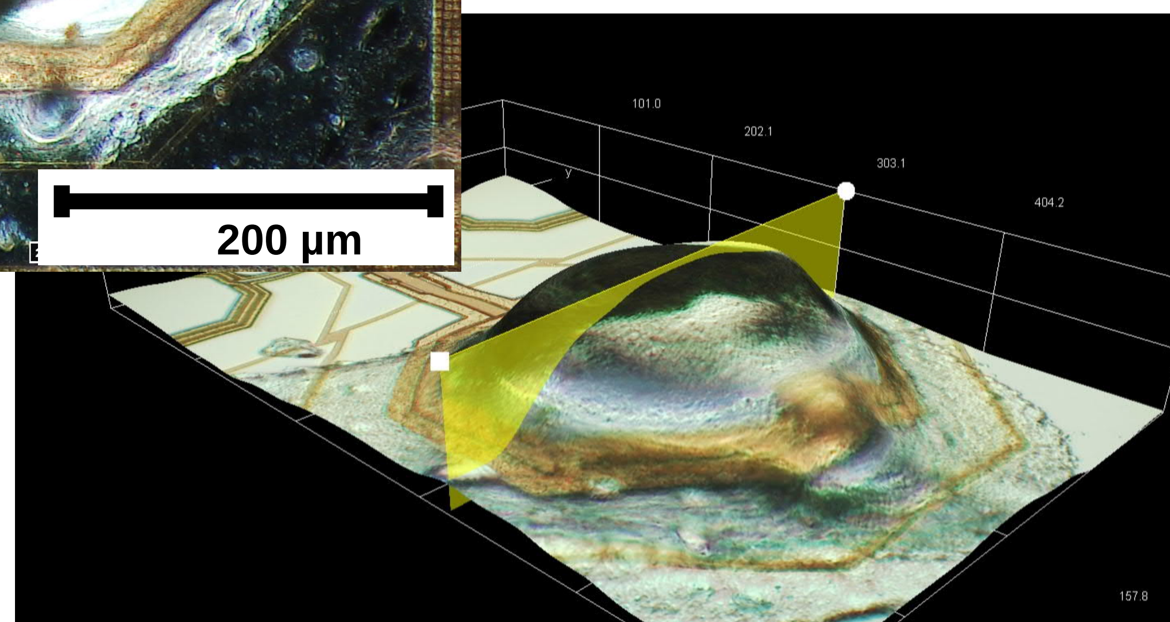
BDPA sample



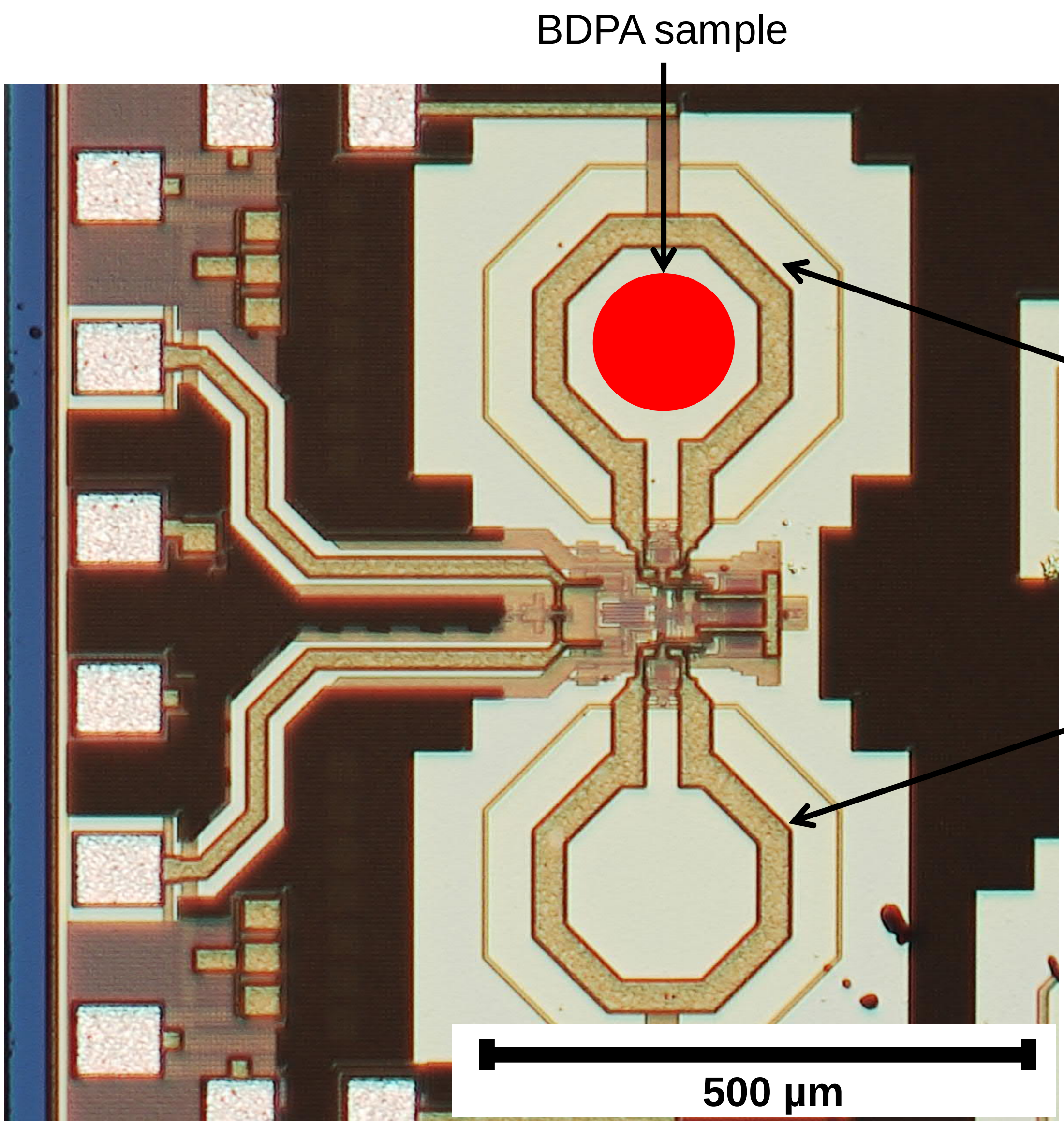
Courtesy of Dr. A. V. Matheoud

Sample installation (10 GHz)

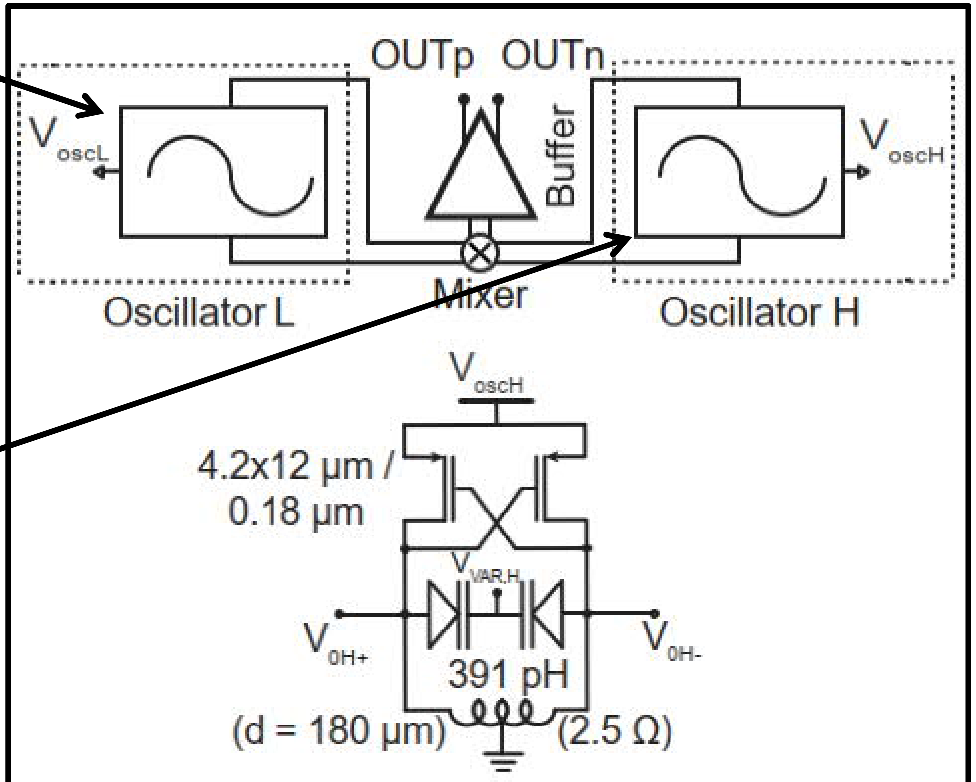




Used of Integrated oscillator f_0=20 GHz B_0=710 mT [7]



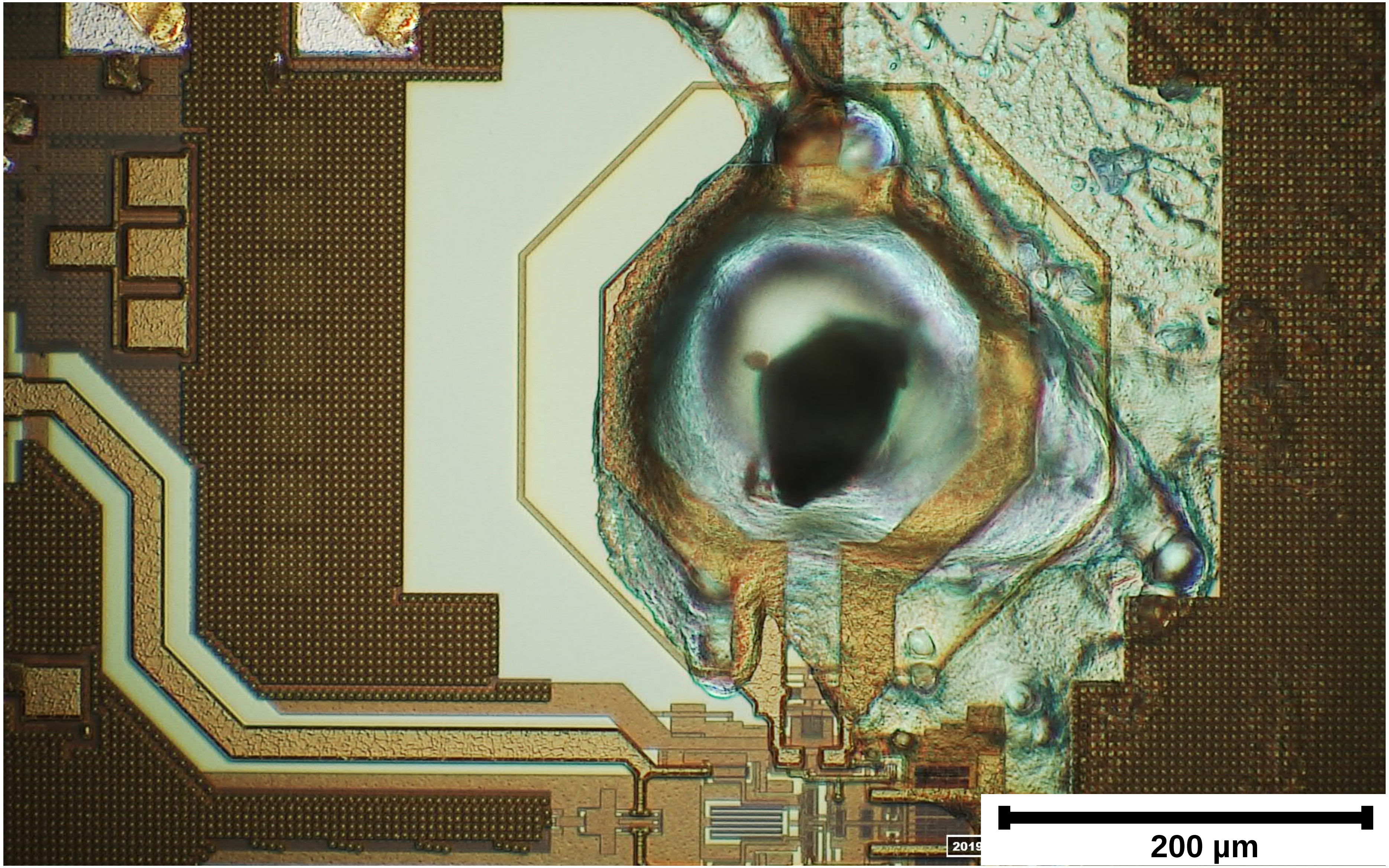
- Cross-coupled LC oscillator structure
- Variable frequency with varicap
- Output freq. 18.5-20.2 GHz



Courtesy of Dr. A. V. Matheoud

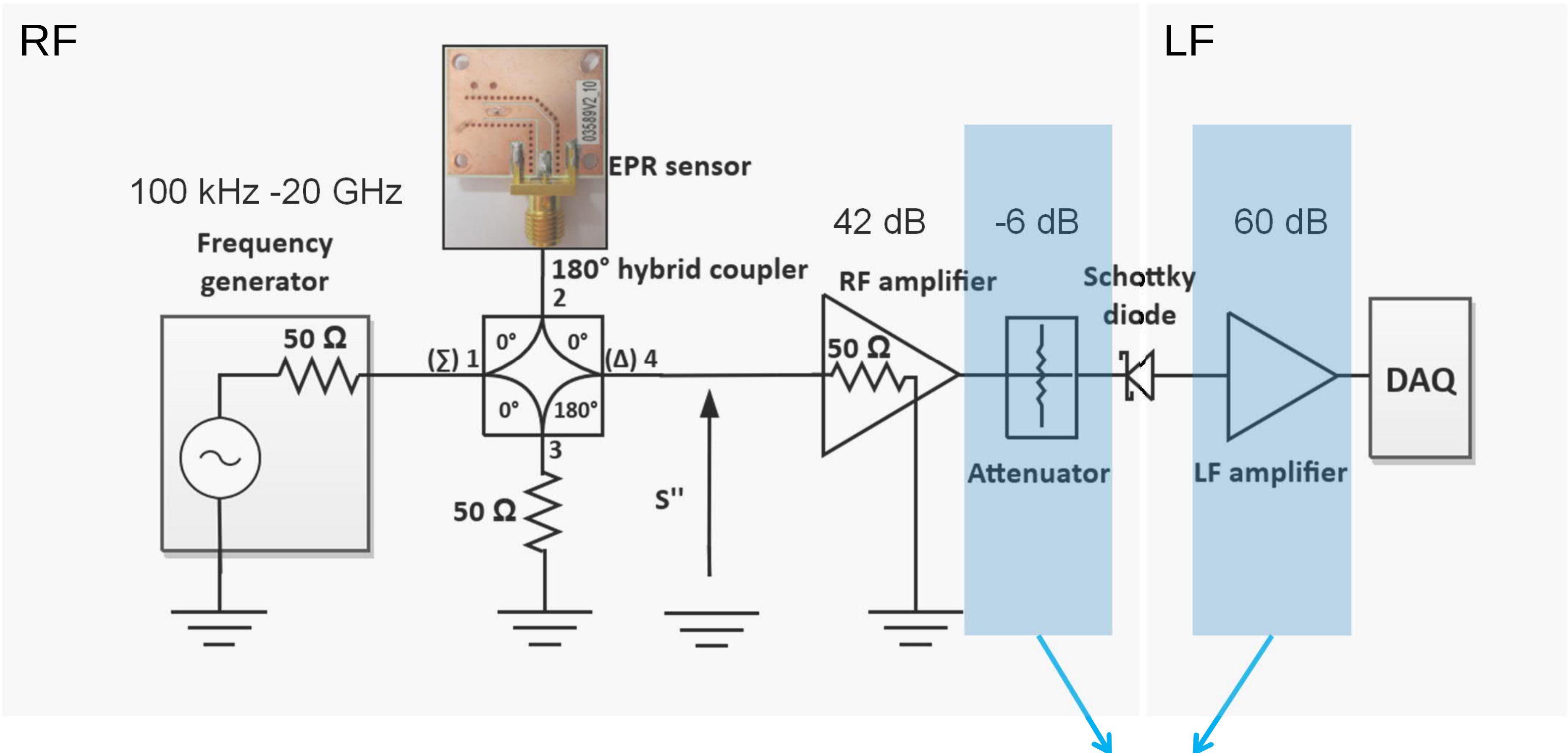
Design: Oscillators (5/5)

Sample installation (20 GHz)



Design: Amplitude detection (1/2)

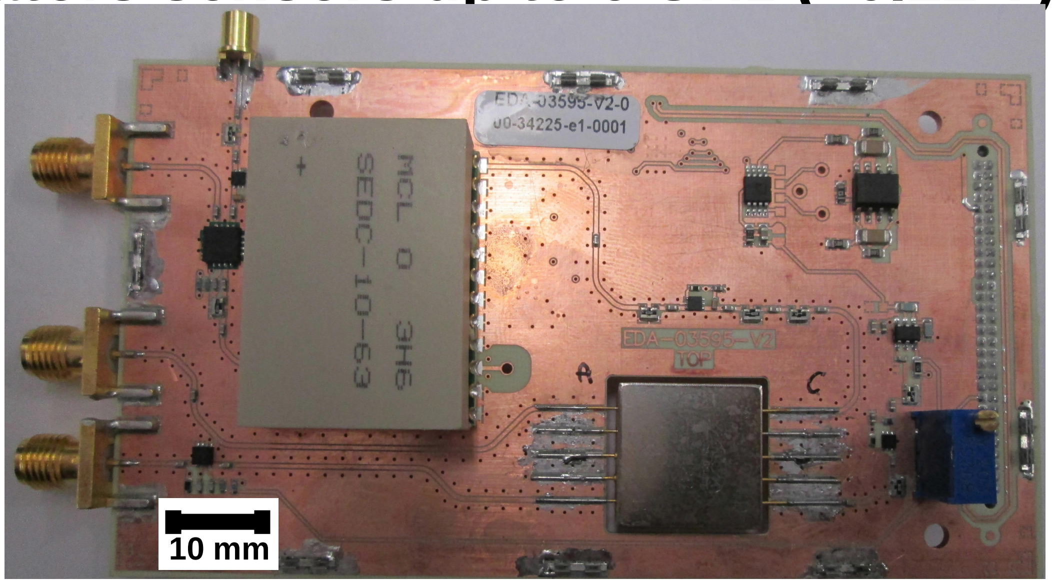
➔ Resonators



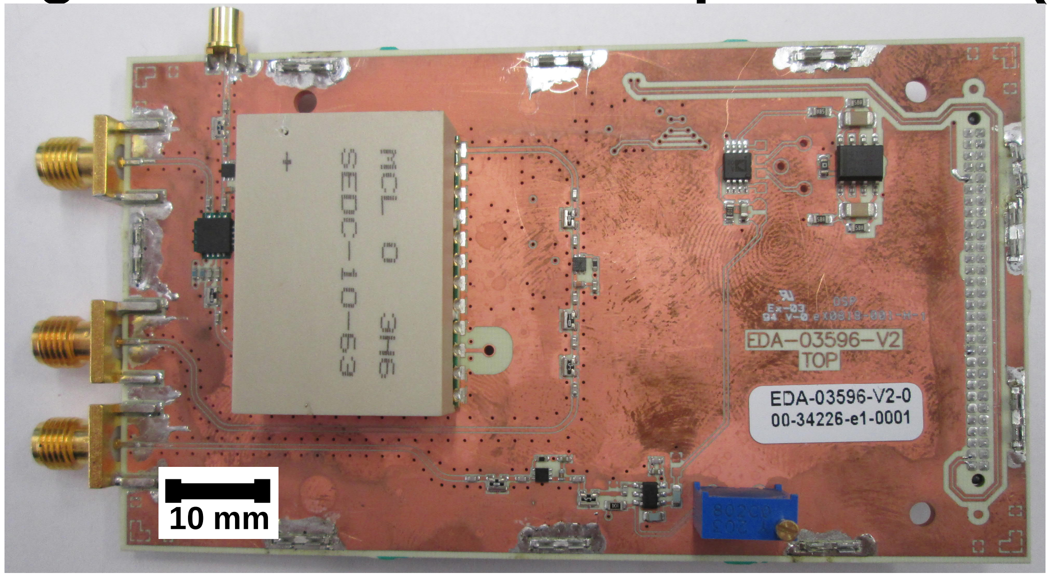
Only for the EPR (BDPA) sample

Design: Amplitude detection (2/2)

→ **For resonators sensors up to 6 GHz (~0.22 T)**

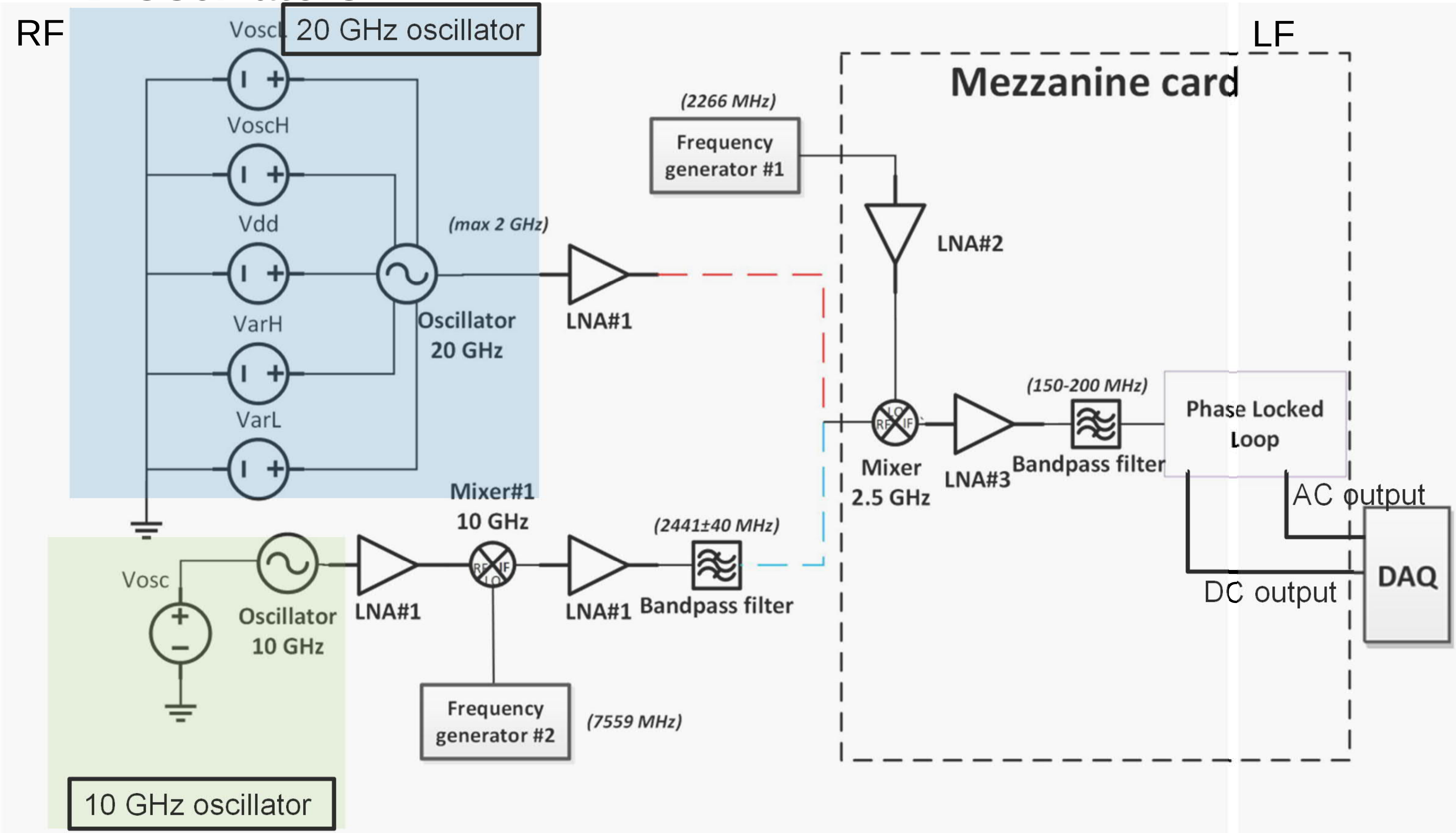


→ **For coupling structure sensors up to 6 GHz (~0.22 T)**

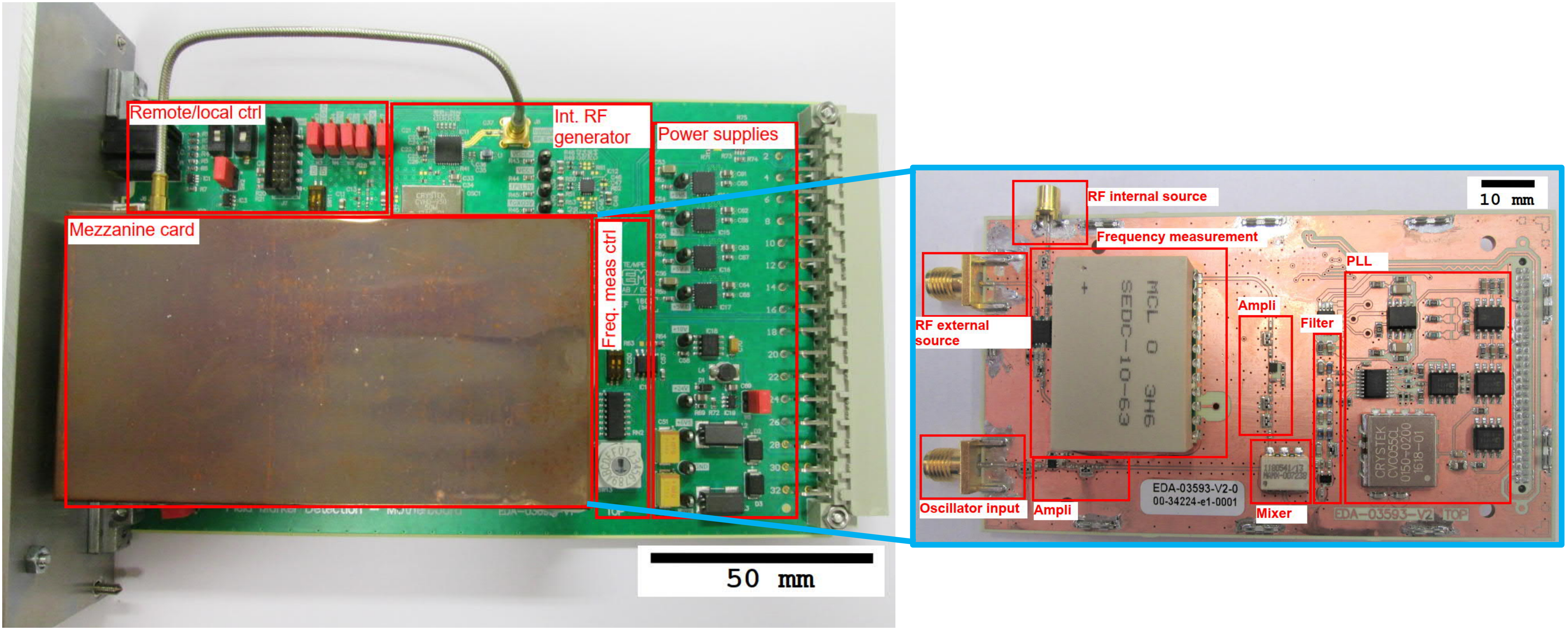


Design: Frequency detection (1/2)

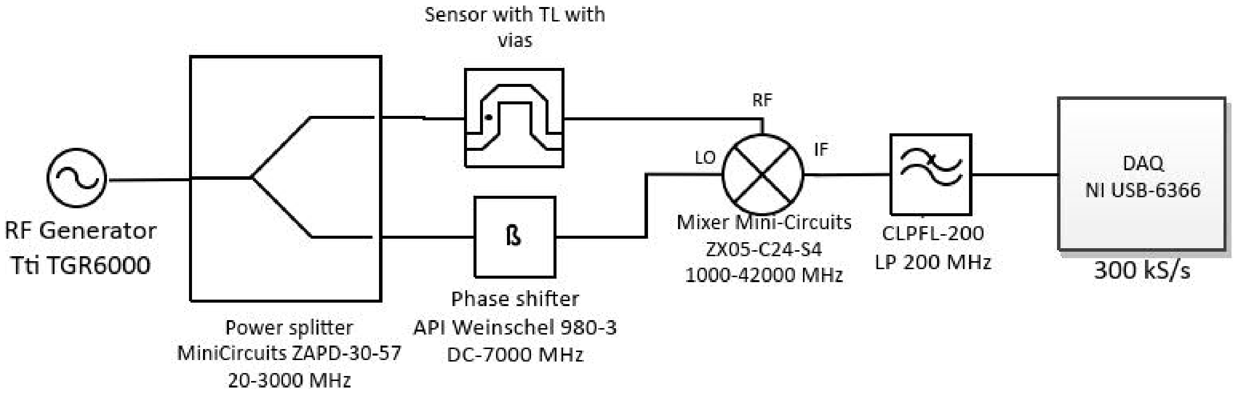
➔ Oscillators

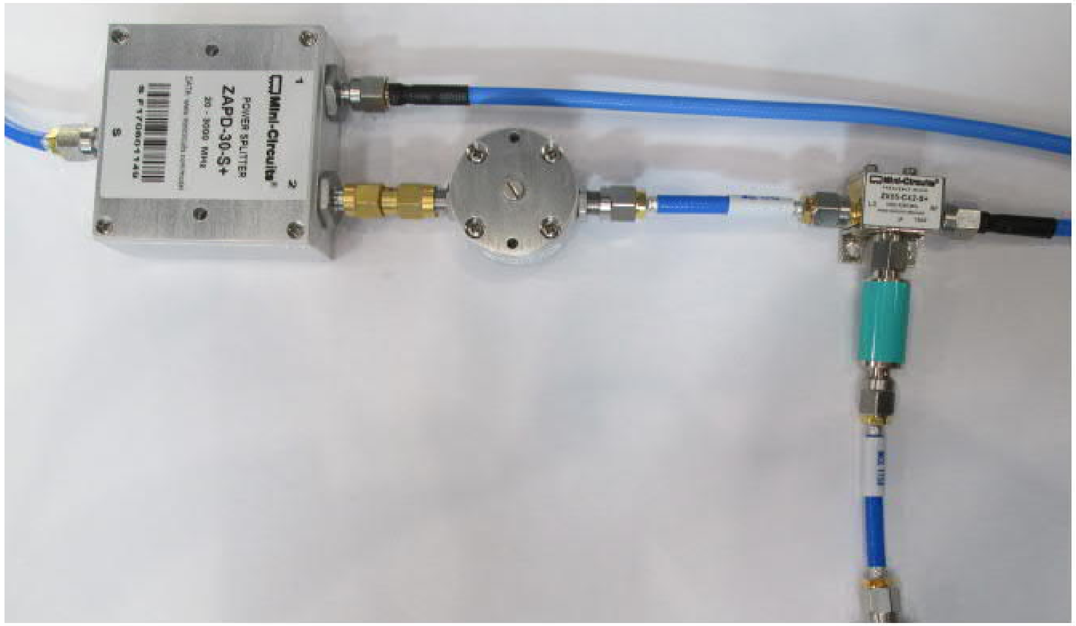


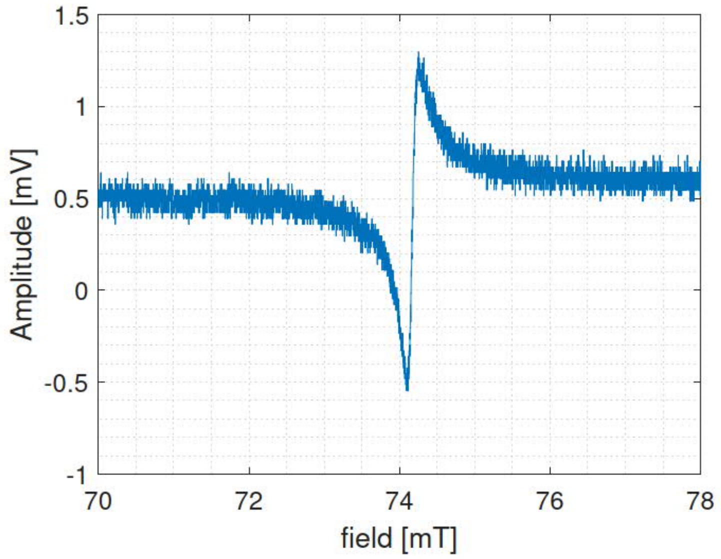
➔ Electronic board with PLL mezzanine card



➔ Phase detection used with transmission line

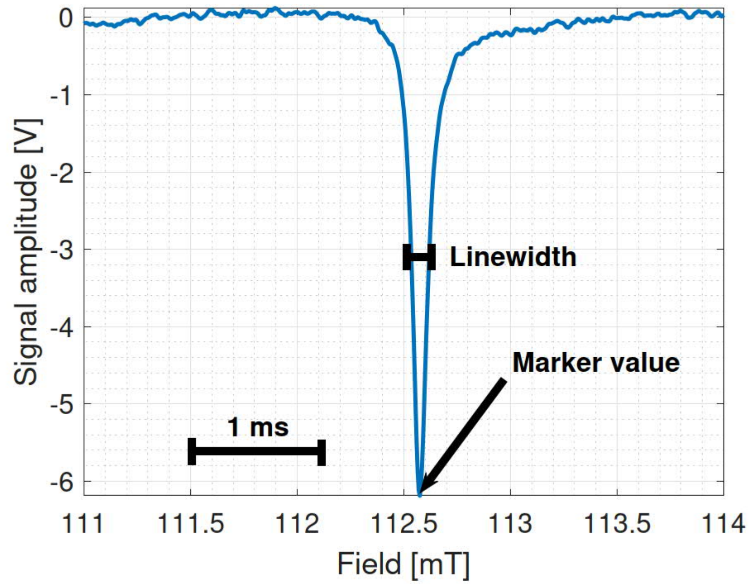






➔ Typical ESR signal in marker mode (sweep B_0, fixed f_1)

Amplitude detection



Frequency detection

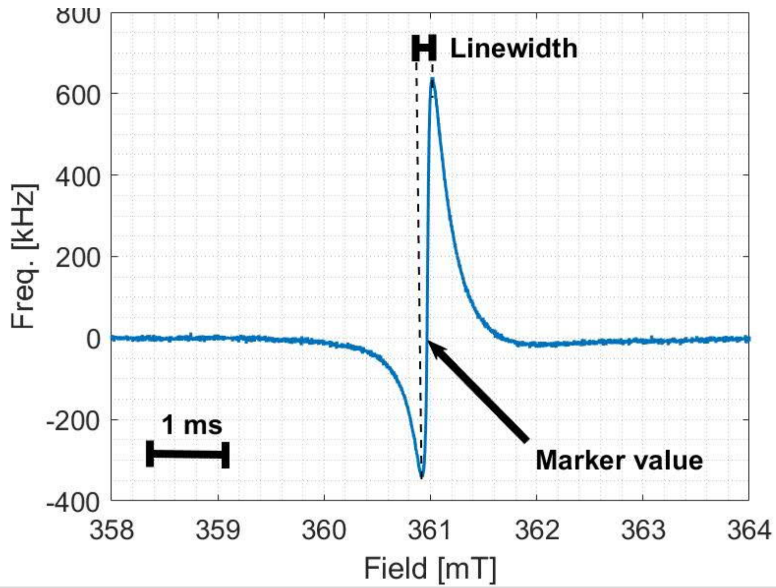


Figure-of-merit:

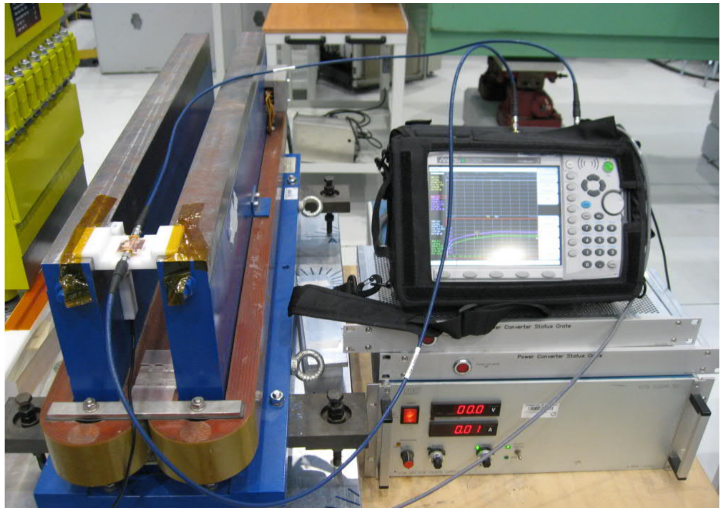
1. The signal-to-noise ratio
2. The shape distortion
3. The marker value
4. The linewidth
5. The resolution

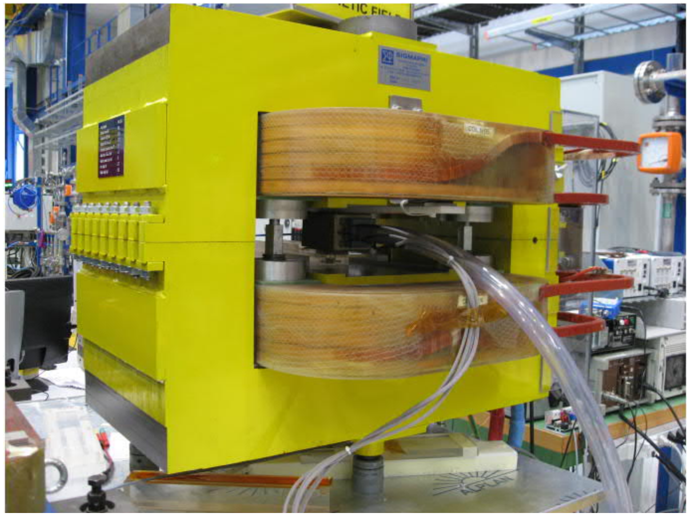
Signal affected by

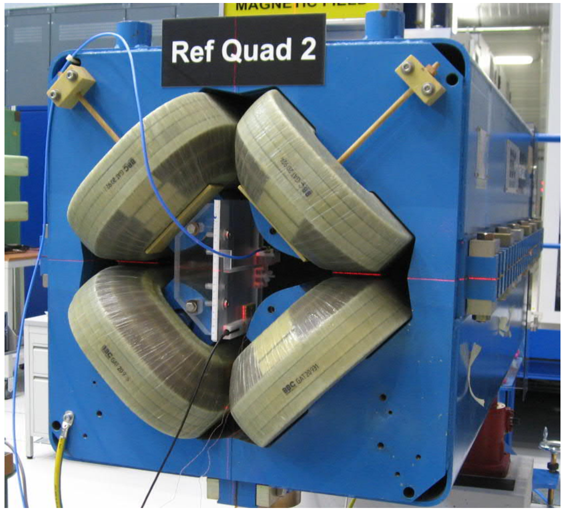
- Gyromagnetic ratio (absolute calibration)
- Temperature
- Ramp rate
- Field direction
- Gradient

Design: Calibration benches

➔ **Characterization steps**







- The temperature stable axis

- Effective gyromagnetic ratio
- The resolution
- Temperature dependency
- Ramp rate dependency
- Field direction dependency

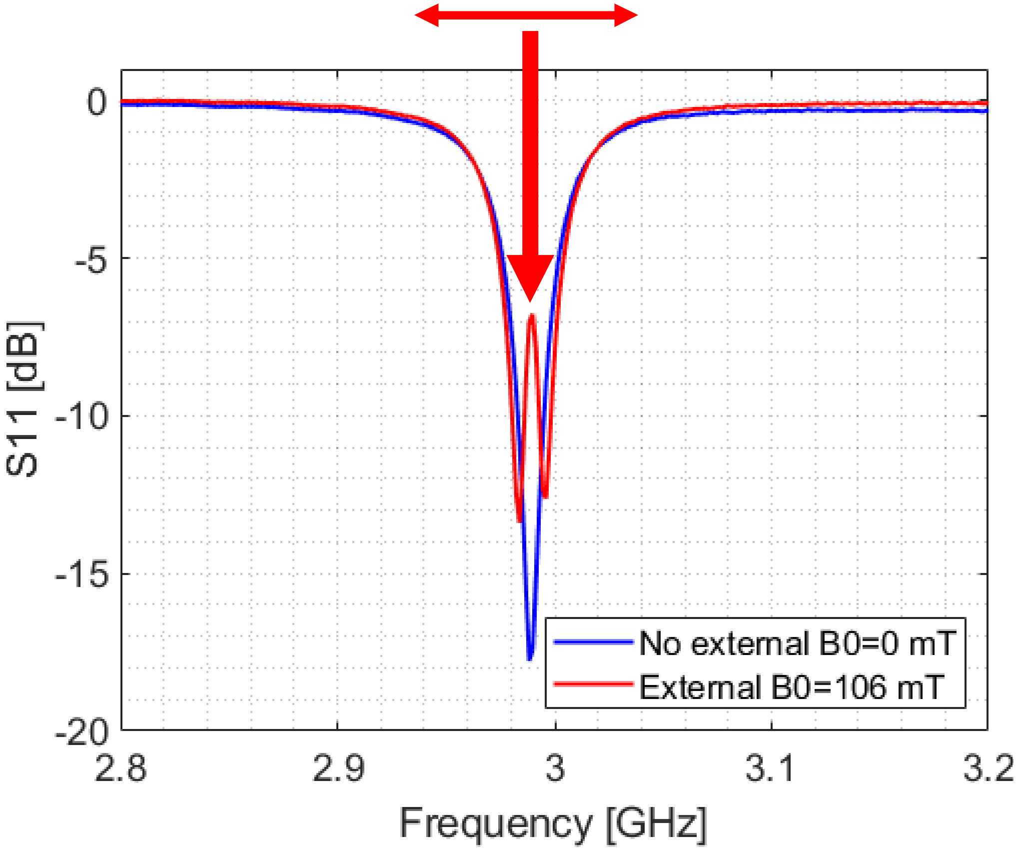
- Gradient sensitivity

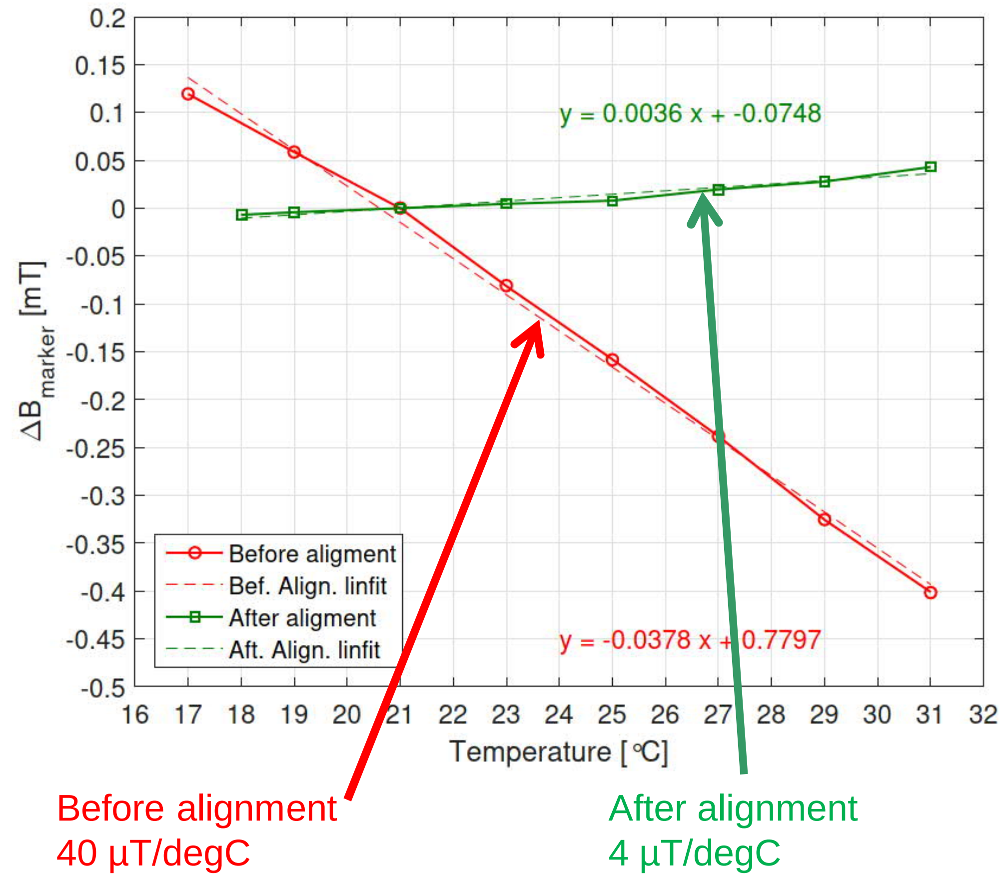
Static B_0 field

Time-transient B_0 field

➔ Temperature stable axis alignment (fixed B_0, sweep f_1)

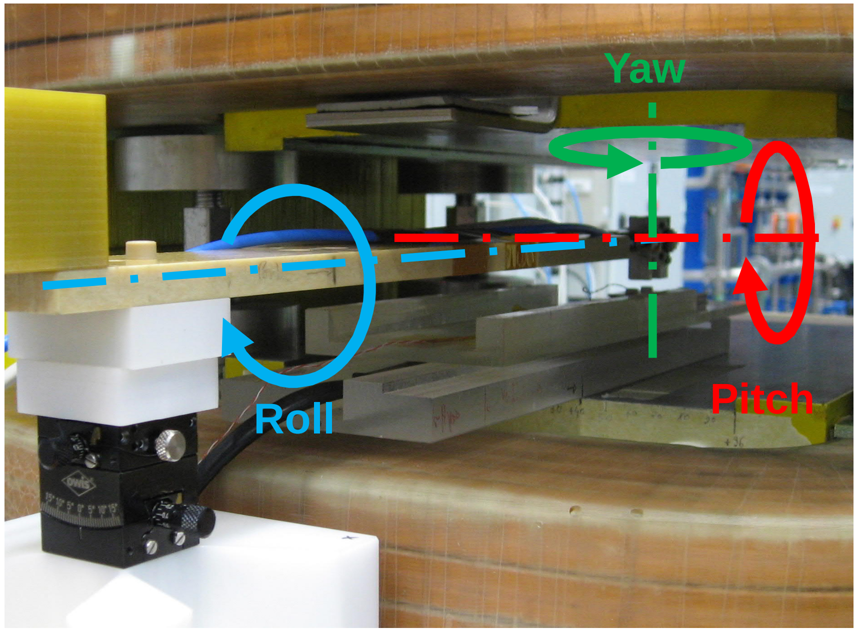
Resonance peak position changes with temperature when sphere is not aligned

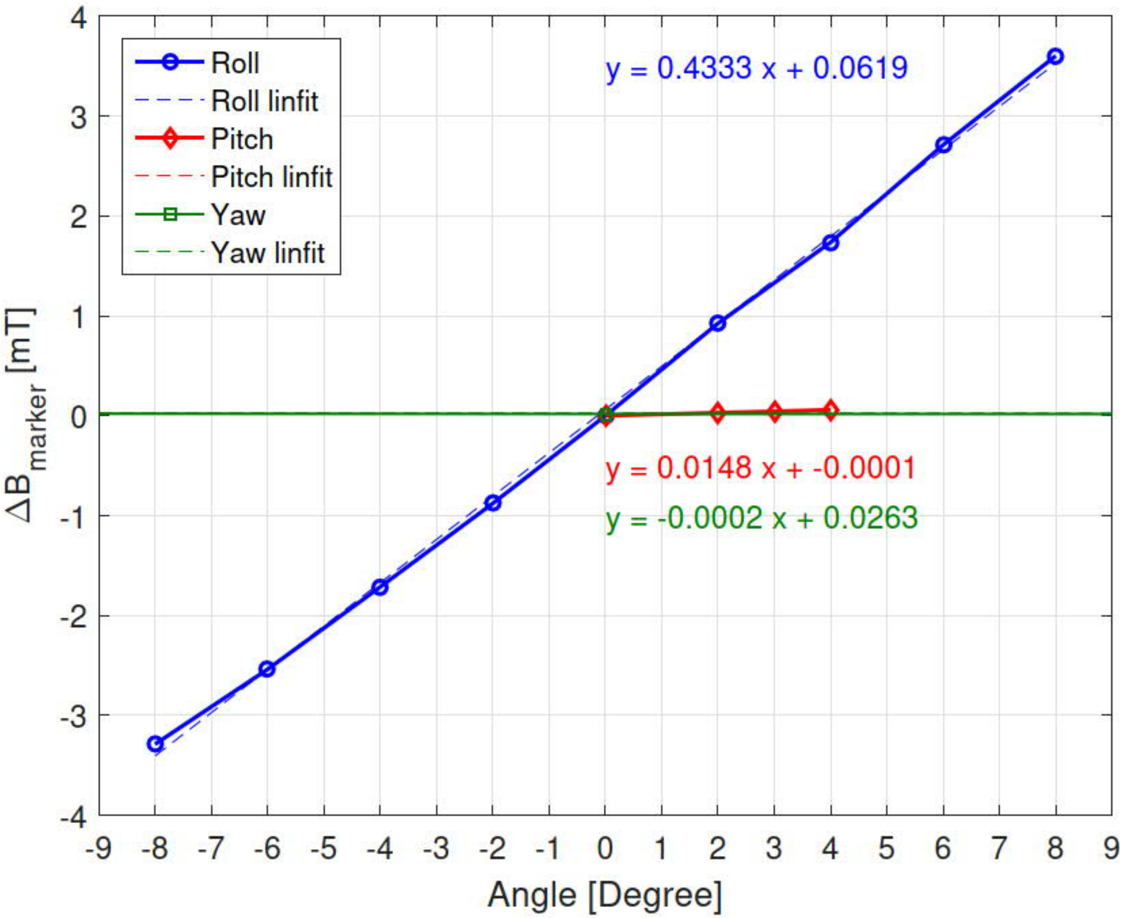




=> Temperature sensitivity is improved by an order of magnitude

➔ **Field direction effect**



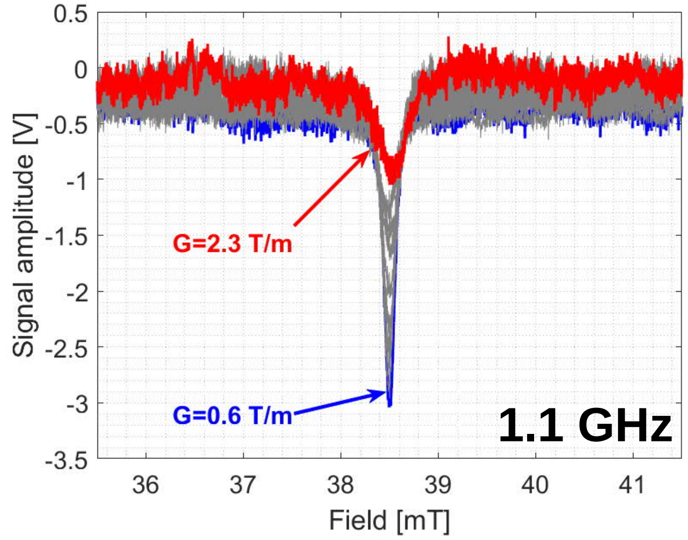


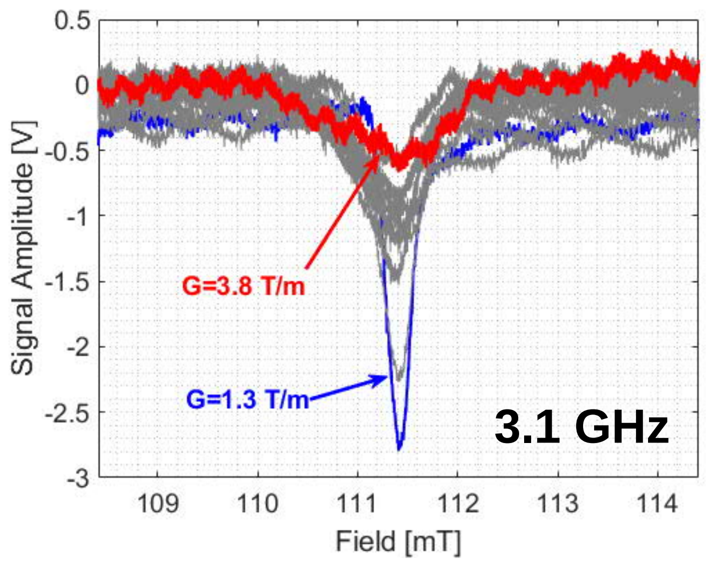
=> Relevant influence on the roll angle by 430 µT/deg

FMR sensors are insensitive to field ramp rates up to 5 T/s and gradients up to 12 T/m

➔ Gradient effect

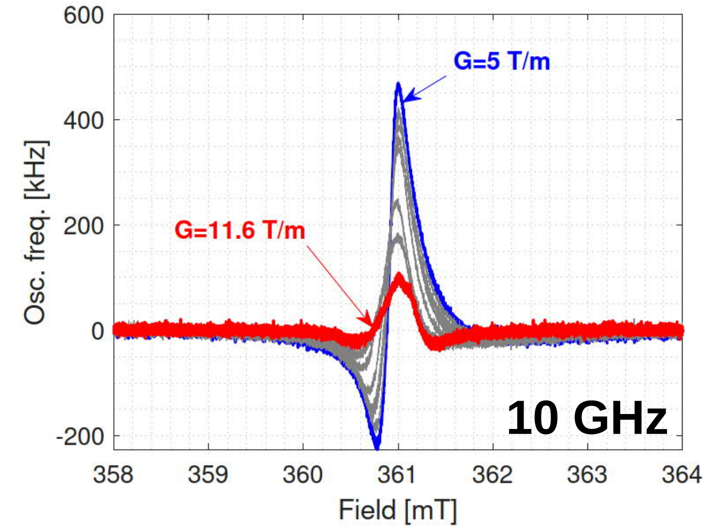
Resonators

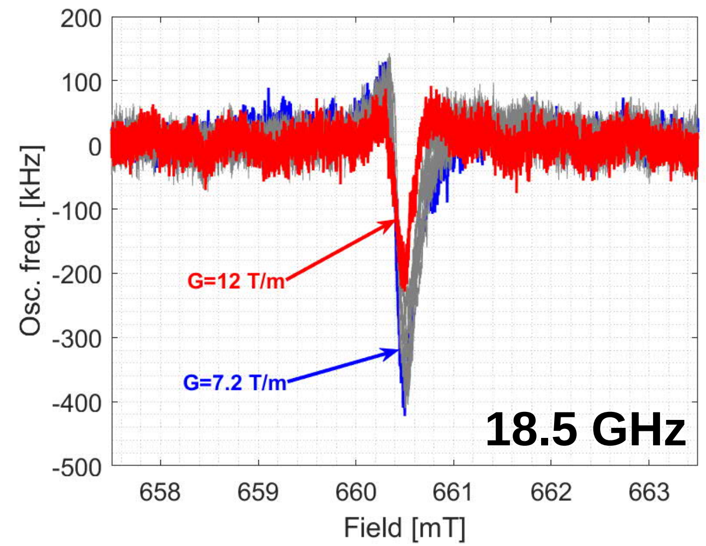




=> Able to measure gradient up to 2 T/m

Oscillators

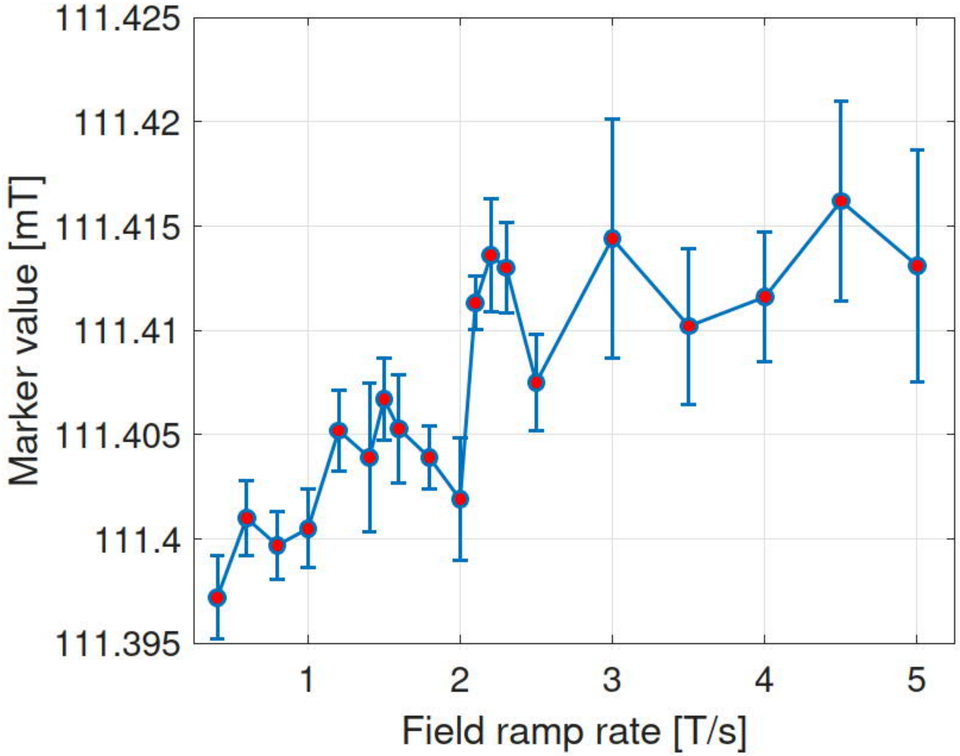




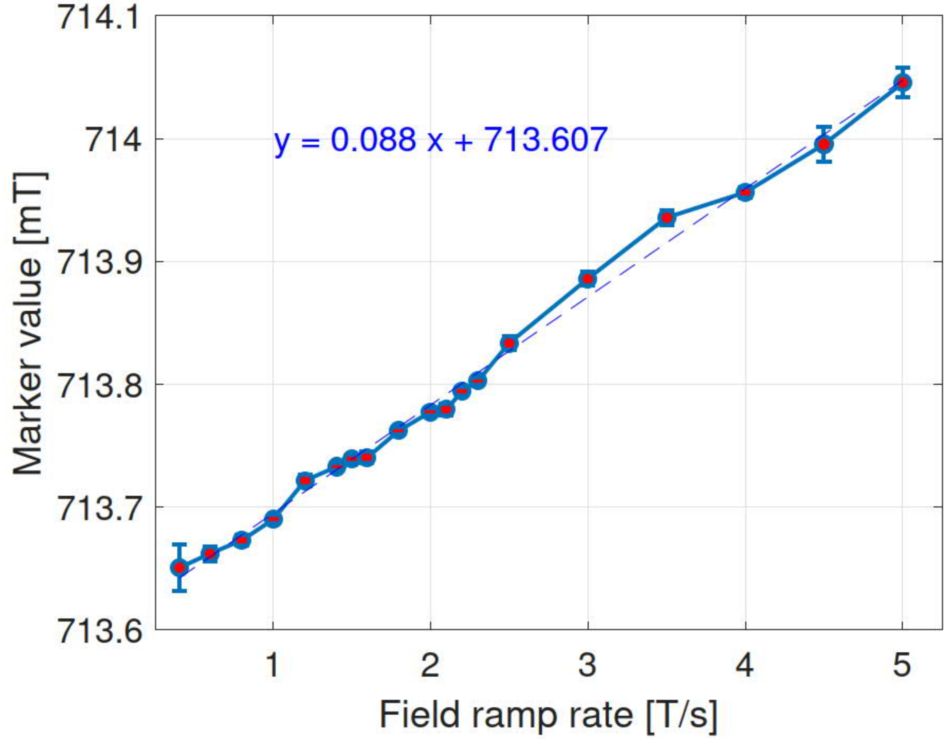
=> Able to measure gradient up to 12 T/m

➔ **Ramp rate effect ($\dot{B}$)**

Resonators



Oscillators



Relevant marker value variation function of by field ramp rate with the 20 GHz oscillator

=> Electromotive forces on the varicaps and power supplies voltage

Results: performance summary

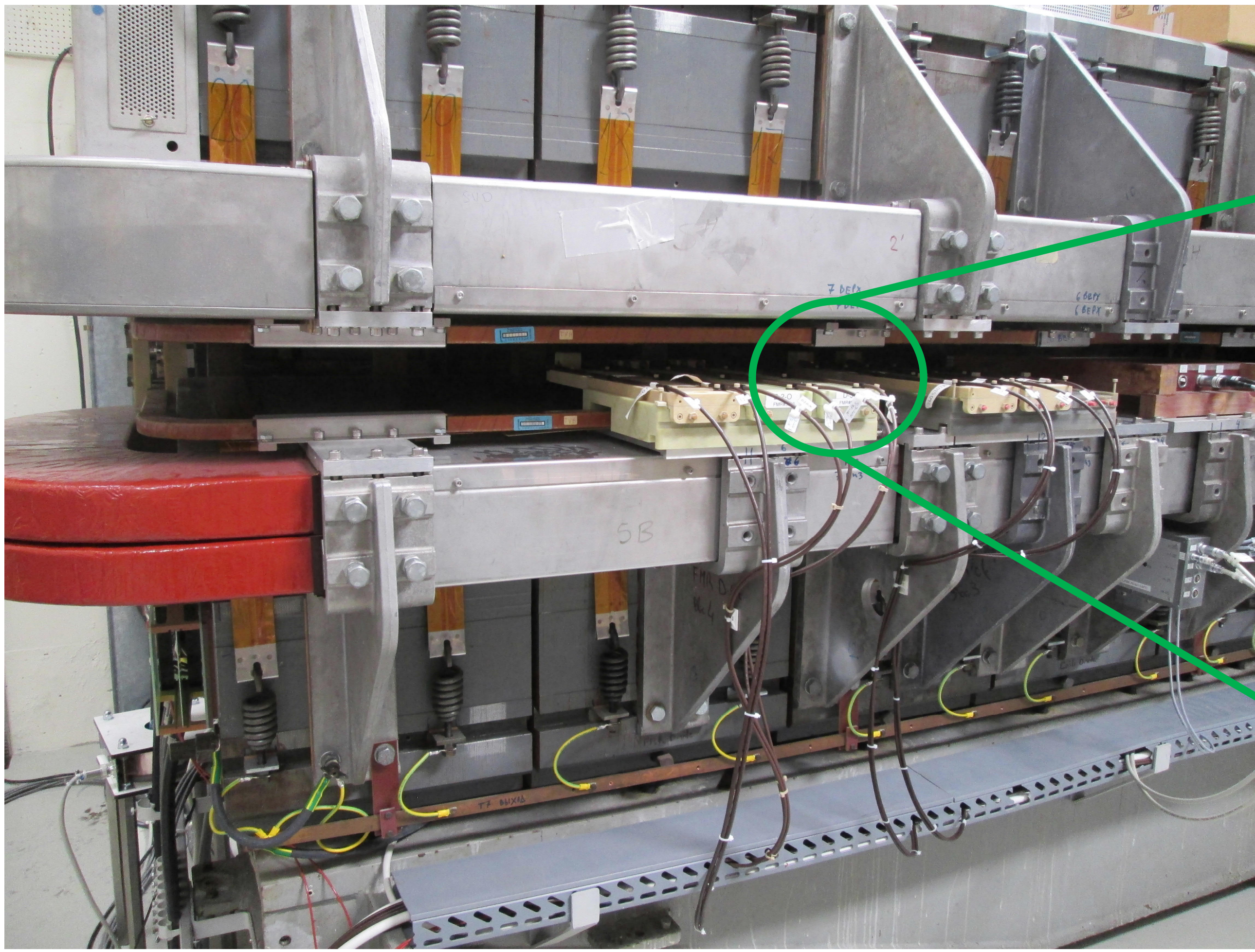
Parameters	FMR 1 GHz Resonator	FMR 3 GHz Resonator	EPR 1 GHz Resonator	EPR 3 GHz Resonator	EPR 10 GHz Oscillator	EPR 20 GHz Oscillator
Sample material	GaYIG	GaYIG	BDPA	BDPA	BDPA	BDPA
Operating frequency (MHz)	1109	3050	1078.9	3123	10111.37	20000 [a]
B_m (mT)	35.9	106.3	38.52	111.41	361.01	713.65
B_m tuning range (mT)	-	-	-	-	-	660-720
Linewidth (μT)	320	370	94	85	97	121
Effective γ (GHz/T)	28.29	28.69	28.01±0.01	28.03±0.01	28.01±0.01	28.02 [a]
Sample volume (μm^3)	14.1×10^3	14.3×10^3	63×10^6	160×10^6	1.2×10^6	0.07×10^6
$\dot{B}$ sensitivity (μT/(T/s))	<3	<3	4	4	<3	90
Gradient sensitivity (μT/(T/m))	-56	-	160	480	39	<10
Maximum gradient (T/m)	1.2	1.5	1.2	1.5	12	12
Maximum field inhomogeneity (m^{-1})	31	13	31	13	25	17
Temperature sensitivity (μT/°C)	3.6	2.2	4.8	7	-	-
Field direction sensitivity ψ (μT/°)	433	368	<1	<1	<1	<1
Resonator sensor sensitivity (V/T)	4256	2286	47450	90800	-	-
Resonator noise floor (V/Hz$^{1/2}$)	3.2×10^{-6}	3×10^{-6}	0.26×10^{-3}	0.2×10^{-3}	-	-
Oscillator sensor sensitivity (Hz/T)	-	-	-	-	31.7×10^9	17.2×10^9
Oscillator noise floor (Hz/Hz$^{1/2}$)	-	-	-	-	3	35
Resolution (nT/Hz$^{1/2}$)	0.7	1.3	5.5	2.2	0.095	2
Bandwidth (kHz)	150	150	100	100	160	160
Integrated resolution (μT_{RMS})	0.3	0.5	1.7	0.70	0.04	0.8
SNR (-)	1620	750	40	100	270	30

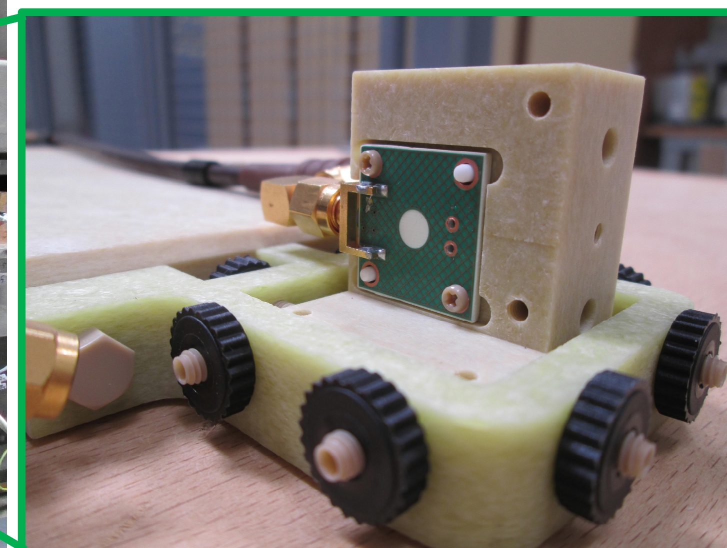
[a] The 20 GHz oscillator has no direct frequency output. As a consequence, the oscillation frequency and the effective γ cannot be measured. The reported oscillation frequency is computed measuring the magnetic field with an NMR magnetometer and an induction coil and assuming an effective $\gamma = \gamma_{BDPA} =$ 28.02 GHz/T.

Low performance | Medium performance | high performance

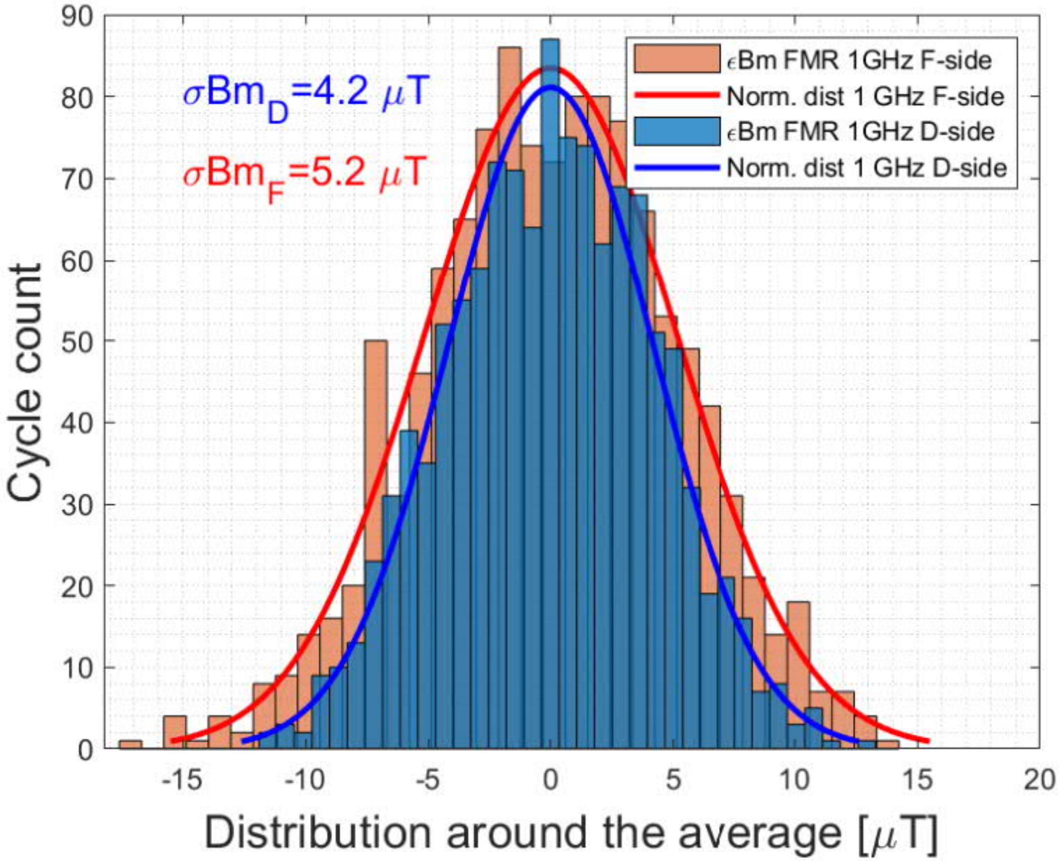
Experimental validation: FMR sensor in PS

FMR sensor at 36 mT (1 GHz) is installed in the focusing and defocusing sides of the PS reference magnet MU101





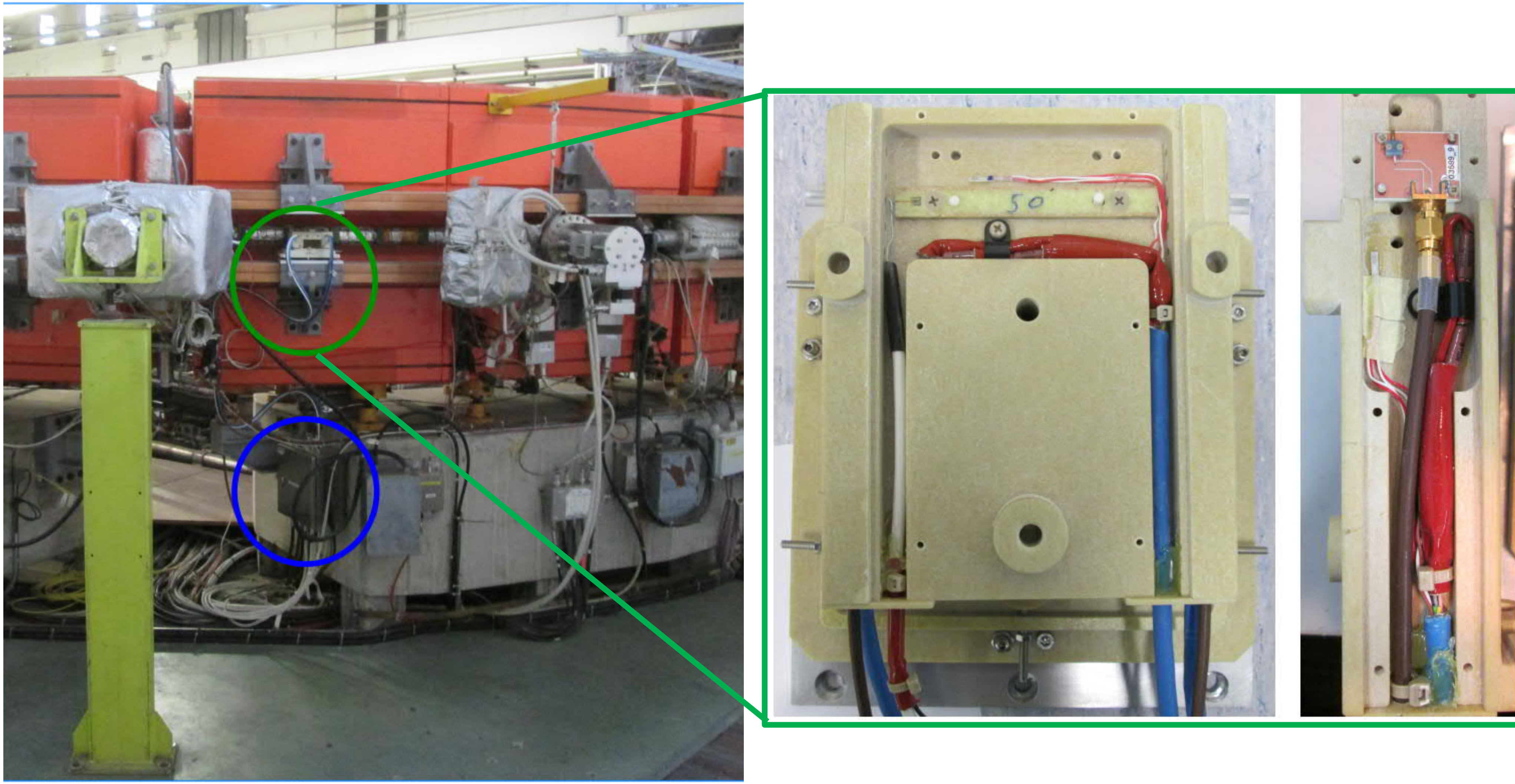
FMR sensor at 36 mT (1 GHz)



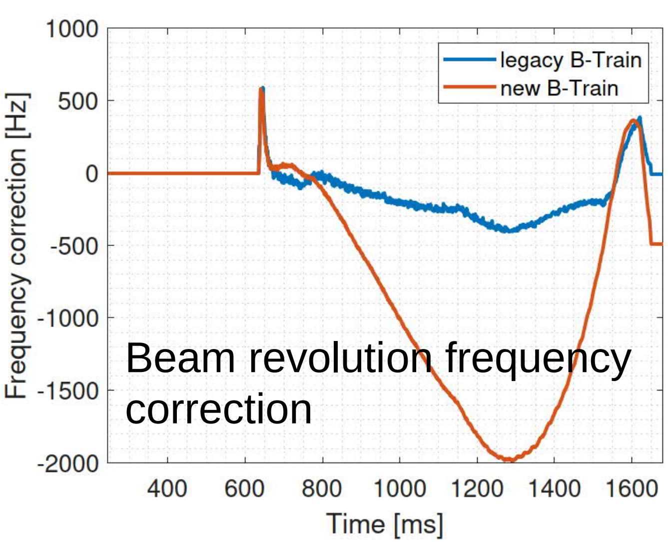
=> Reproducibility by about 5 µT corresponding to 5 x 10^{-5} <u>at injection</u>, that is, within the PS operation requirement

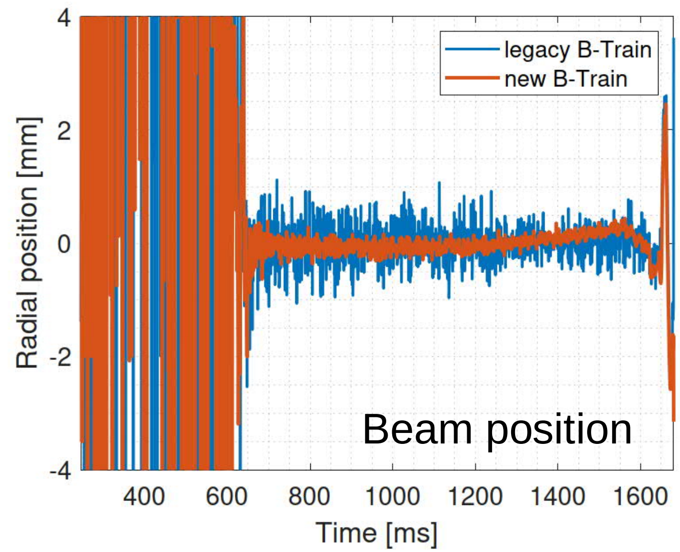
Experimental validation: LEIR B-Train system (1/2)

The FMR sensor at 106 mT (3 GHz) is used in the fringe field of the main bending magnet



Experimental validation: LEIR B-Train system (2/2)





New B-train measurement:

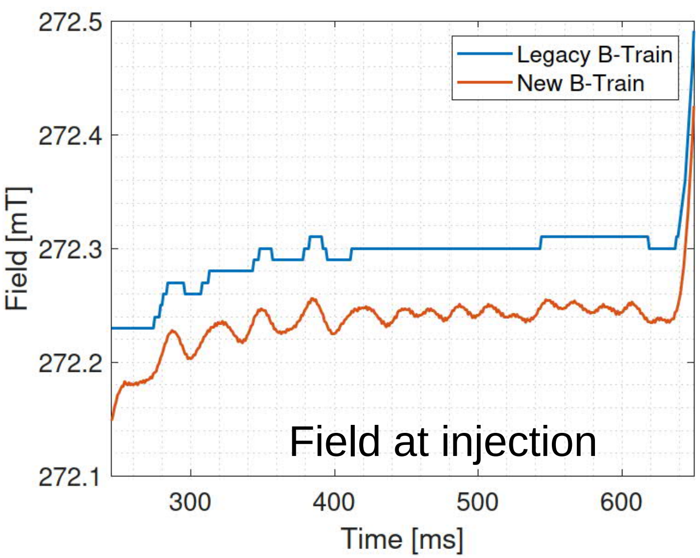
⇒ **Resolution from 10 to 0.2 μT**

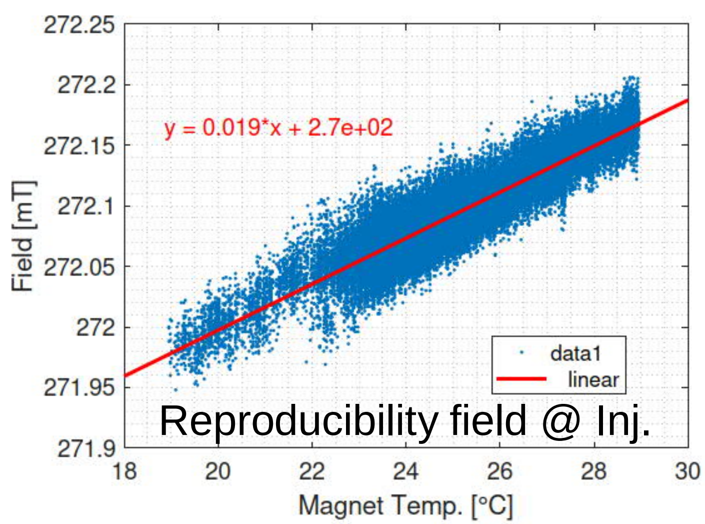
⇒ **Radial position stability from 0.6 to 0.1 mm RMS**

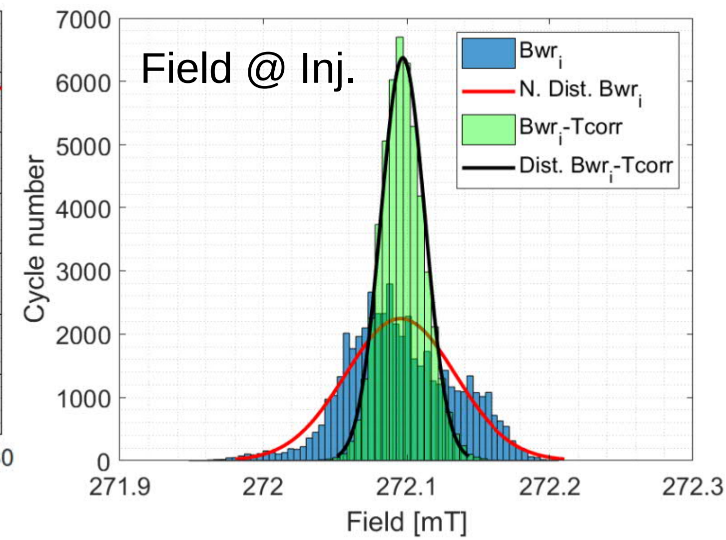
⇒ **Max field error 1.5 mT (0.2%)**

Impact of new marker:

⇒ **Cycle-to-cycle reproducibility from several 100 μT down to 38 μT (1.4 x 10^{-4})**







Conclusions and future perspectives

- **The proposed ESR sensors have a reproducibility better than 1.4 x 10^{-4} . They operate in a field range up to 0.7 T, in a field gradient up to 12 T/m and with ramp rate up to 5 T/s.**
- **FMR sensors were implemented and validated on two B-Train systems.**
- **The parametric model of the waveguide resonator allows easy adaptation to different field marker levels.**
- **Extended versions of the EPFL's oscillator architecture could be used to measure fields above 1 T.**
- **The implementation of a modulation coil on the marker sensor with an adapted detection electronics, would allow operation in static background field.**

Thank you for your attention

Questions?

Acknowledgements

- **The B-Train team M. Amodeo, M. Colciago, V. Di Capua, C. Grech, D. Oberson, A. Parrella, M. Roda, J. Vella Wallbank**

- **The B-Train users**
  - **F Boattini, J. L. Gomez Costa, Q. King (TE/EPC)**
  - **P. Odier, S. Thoulet (BE/BI)**
  - **S. Albright, M. E. Angoletta, F. Caspers, H. Damerau, A. Findlay, M. Jaussi, D. Perrelet, N. Pittet (BE/RF)**
  - **M. Lipinski (BE/CO)**

- **The PS team D. Cotte, M. Delrieux, O. Hans, A. Huschauer, J. M. Nonglaton, R. Maillet, G. Sterbini**

- **The LEIR team R. Alemany Fernandez, N. Biancacci, A. Saa Hernandez, S. Hirlander**

- **The wire bounding and QART Labs**
  - **G. Corradini (EPFL)**
  - **A. La Rosa, F. Manolescu, I. Mcgill (EP/DT)**

References

[1] E. Feldmeier, T. Haberer, A. Pters, C. Schoemers, and R. Steiner, *“Magnetic field correction in normal conducting synchrotrons,”* in IPAC. Kyoto: IPAC, 2010.

[2] C. Grech, R. Avramidou, A. Beaumont, M. Buzio, N. Sammut and J. Tinembart *“Metrological Characterization of Nuclear Magnetic Resonance Markers for Real-time Field Control of the CERN ELENA Ring Dipoles,”* IEEE Sensors Journal, 2018, 18, 5826-5833

[3] P. Arpaia, M. Buzio, F. Caspers, G. Golluccio, and D. Oberson, *“Metrological Performance of a Ferrimagnetic Resonance Marker for the Field Control of the CERN Proton Synchrotron,”* IEEE Transactions on Applied Superconductivity, vol. 22, no. 3, pp. 9 001 904–9 001 904, jun 2012.

[4] H. Gebhardt and E. Dormann, *“ESR gaussmeter for low-field applications,”* Journal of Physics E: Scientific Instruments, vol. 22, no. 5, pp. 321–324, May 1989.

[5] E. Tiesinga, P. J. Mohr, D. B. Newell, and B. N. Taylor, The 2018 CODATA Recommended Values of the Fundamental Physical Constants (Web Version 8.0), National Institute of Standards and Technology

[6] A. Matheoud, N. Sahin Solmaz, L. Frehner, and G. Boero, “Microwave inductive proximity sensors with sub-pm/ Hz resolution,” Sensors and Actuators A: Physical, vol. 295, 05, 2019.

[7] A. V. Matheoud, “Electron Spin Resonance detectors from 400 MHz to 360 GHz,” Ph.D. dissertation, EPFL, Lausanne, 2019.

[8] A. Beaumont, D. Giloteaux, A. V. Matheoud, M. Buzio and G. Boero, “Electron paramagnetic resonance field sensors for Particle accelerators,” submitted to Review of Scientific Instruments, 2020.