CAPTEURS MAGNETOMETRIQUES

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TECHNOLOGICAL AND INDUSTRIAL RESEARCH INSTITUTE

DIVISION LETI
SYSTEMS DEPARTMENT

WEAK MAGNETIC FIELDS METROLOGY

In the Systems Department (DSYS), the LETI division has developed high sensitivity magnetic field detectors, which have been used for a wide variety of purposes:

- geological prospection (D. LETI uses the trademark GAMCIS for this activity);
- military detection;
- study of the magnetic fields generated by the electrical activity of the brain;
- recent developments include scientific applications in space.

Measuring principles

These detectors can be classed in two categories:

Mont-Rachais measuring site (Chartreuse).

■ Resonance magnetometers

These instruments are sensitive to the modulus of the magnetic field, the resonance is either nuclear or electronic and can be amplified (or not) by an electronic or optical pumping process.

Among those, the studies are focused on: the NMR magnetometer with electronic pumping, the optically pumped ESR magnetometer (4 He gas), the ESR magnetometer using organic materials. The detectors used are field-frequency transducers for which the proportionality factor is a constant.

Flux-meter for measuring low frequency magnetic fields. Manufactured under licence by the companies ARPE and ICAP (developed by D. LETI).

■ Vectorial magnetometers

This type of magnetometer gives a reading equivalent to the scalar product between the magnetic field vector and the characteristic vector of the probe oriented in the direction to be measured. The physical principles employed in these detectors are:

- Faraday's law (induction): a changing magnetic field induces a voltage in a coil;
- Magnetostriction: a material is deformed by a magnetic field and is measured by optical interferometry;
- Superconductivity;
- The saturation of a soft magnetic material.

Development work concerning the last two mentioned principles was stopped in 1985: however, these detection methods are still used as tools.

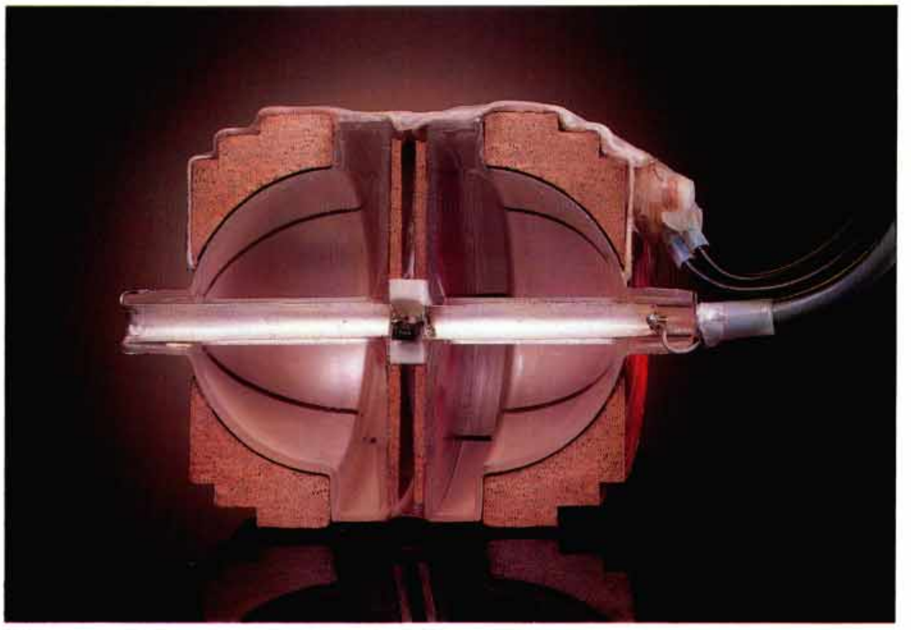
The table below shows the principal characteristics of magnetometers developed by the D. LETI.

Magnetometers developed by D. LETI

Type of magnetometer	Field range	Output	Frequency range	Resolution
NMR (electronic pumping)	20 to 70 μT (earth's field)	Frequency: 1 to 3 kHz	0 - 0.1 Hz	0.01 nT
ESR (optical pumping)	,,	Frequency: 0.7 - 2 MHz	0 - 1 Hz	0.01 nT
ESR (solid material)	,,	,,	0 - 1 kHz	1 nT
Induction	1 nT - 100 μT	Voltage	0.5 Hz to 10 kHz	0.01 nT @ 10 Hz
Magnetostriction	0 - 100 μT	Length → voltage	0 - 10 Hz	0.1 nT
Superconductor	0 - 10 μT	Voltage	0 - 10 kHz	0.0001 nT

Measurements

These magnetometers require specialized measuring facilities for their construction and calibration. The D. LETI facilities are situated in the laboratories of the C.E.N. Grenoble, and at an out-station situated in the Chartreuse mountains, chosen for its geological situation and its isolation from urban perturbations.

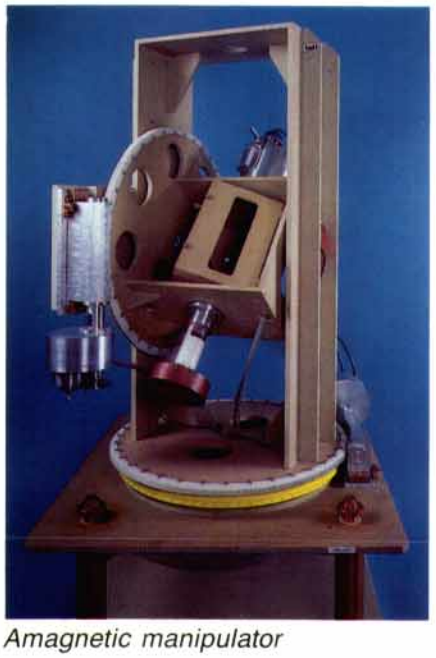


NMR probe. The company CROUZET is the licensee for space and military applications.

The following table shows the equipments currently used, with their characteristics.

Magnetic field measuring equipments used by D. LETI

Equipment	Site	Range	Performance	Function
SQUID magnetometer	CENG	0-10^{-3}Am^2	10^{-10}Am^2	Measurement of induced and remanent fields of samples
NMR low field spectrometer	Rachais	50 μT		Study of radical solutions for NMR probes
ESR low field Spectrometer	CENG	100 μT		Study of materials for ESR probes
Amagnetic manipulator	Rachais	3 axis movement $\pm$ 180°		Isotropic and gyromagnetic studies of probes
Helmholtz coils	Rachais	20-70 μT	Homogeneity 10^{-5} over 1 dm^3	Probe studies
Thermoregulated amagnetic container	Rachais	−40 + 70°C		Study of temperature effects on probes
Helmholtz coils	CENG	0-100 μT 0-1 kHz	Homogeneity 10^{-4} over 10 cm	Magnetometer calibration
Gradient coils	CENG	0-10 mT/m	Linearity 10^{-3} over 1 dm^3	Study of magnetometers in gradient fields
Magnetic shielding	CENG	Volume: several liters	60 dB	Noise measurement of directional magnetometers



Amagnetic manipulator

Sample study using a SQUID magnetometer (developed by D. LETI).

ESR Spectrometer (developed by D. LETI).

Informations:

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COMMISSARIAT A L'ENERGIE ATOMIQUE

DIVISION leti

INSTITUT DE RECHERCHE TECHNOLOGIQUE ET DE DÉVELOPPEMENT INDUSTRIEL

Département Systèmes

RESONANCE PARAMAGNETIQUE ELECTRONIQUE EN CHAMP FAIBLE

La population des spins électroniques d'un matériau soumis à un champ magnétique B_0 statique précessionne autour de celui-ci à une vitesse angulaire ω_0 donnée par la relation de LARMOR :

$$\omega_0 = \gamma \mu_0 B_0$$

où $\gamma = 1.76\ 10^{11}\ s^{-1} . T^{-1}$

et $\mu_0 = 4\pi\ 10^{-7}$ H/m

B_0 est un champ faible, typiquement le champ magnétique terrestre qui varie entre 25 μT et 70 μT.

Dans cette gamme de champ la fréquence de précession des spins va de 0,7 à 2 MHz.

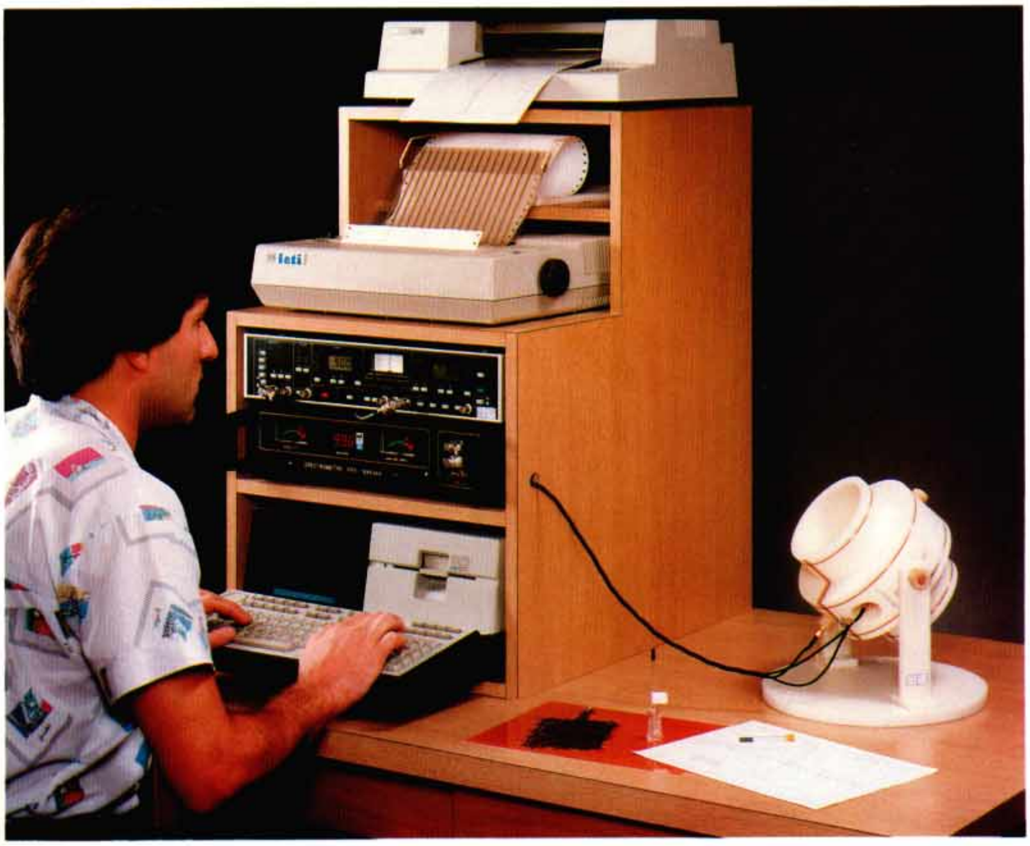
Un système imaginé par BLOCH en 1946 permet la détection de la résonance.

LES MATERIAUX

La magnétométrie RPE utilise un matériau solide possédant des électrons libres. Les qualités requises pour ces matériaux sont :

- une grande susceptibilité magnétique (1 à 4.10^{-4} emu/mole)
- une raie RPE unique (pas de couplage hyperfin)
- une stabilité parfaite dans la gamme usuelle de température (−40 à +70°C).

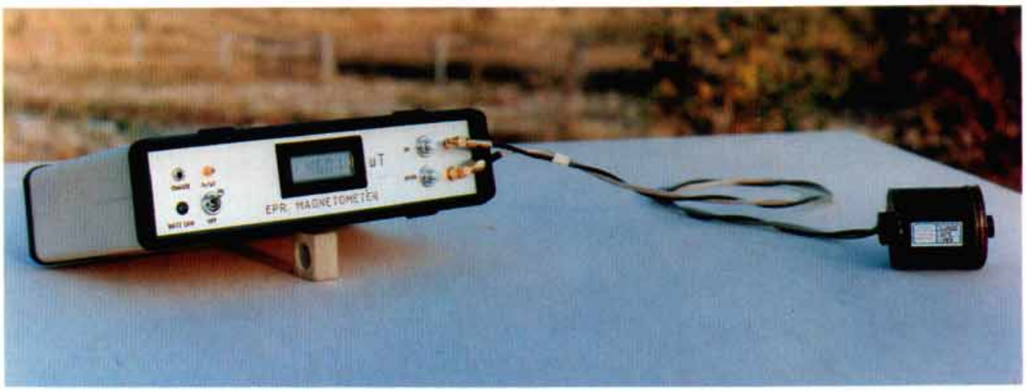
Trois classes de matériaux ont été identifiées. Ce sont des radicaux π neutres, cationiques ou anioniques. L'étude des matériaux pour le magnétomètre inclut leur synthèse, leur caractérisation et leur conditionnement.



LE SPECTOMÈTRE 1,845 MHz

Le spectomètre RPE permet une mesure des performances des matériaux synthétisés même sur de faibles quantités (0,5 mg).
Les grandeurs physiques telles que les temps de relaxation T_1 et T_2 et la susceptibilité magnétique (ou la densité de spin apparent) sont accessibles. Le spectomètre, entièrement automatisé, effectue des mesures en fonction de la modulation, de l'excitation ou au cours du temps à intervalles réguliers.

Une deuxième génération à champ variable (10 - 500 MHz) est envisagée. Celle-ci permettra l'étude quantitative de matériaux semi et supraconducteurs ou encore l'étude d'intermédiaires réactionnels en chimie biologique.



LE MAGNÉTOMÈTRE

La sonde de mesure du magnétomètre est réalisée autour d'un matériau dont la fréquence de résonance des spins électroniques est liée au champ ambiant B_0 par la relation de Larmor : $F_0 = 28$ GHz/T.

La résonance des spins est entretenue par un champ RF dont la fréquence est asservie par une électronique de détection (0,7 à 2 MHz pour la gamme du champ terrestre).

Les caractéristiques de la maquette représentée sur la photographie sont les suivantes :

- mesure du champ total
- lecture : 4 digits, 5 mesures/seconde
- résolution : 10 nT
- précision absolue : 50 nT (0,1 %)
- sonde : volume 50 cm³, masse 100 g
- bande passante : continu à 5 Hz
- tenue au gradient : 50 μT/m
- dérive et coefficient de température : effets inférieurs à la résolution dans la gamme 0 à 50°C
- isotropie : 10 nT sur $\pm$ 85°C autour de l'axe de mesure
- sortie analogique : 0,1 V/μT

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NUCLEAR MAGNETIC RESONANCE PROBE FOR MAGNETOMETERS

The total field N.M.R. magnetometer is capable of measuring very small variations in the earth's magnetic field. Its high sensitivity makes it a very useful detector in the space, military and civil sectors.

The probe is a field/frequency transducer based on the principle of nuclear magnetic resonance amplified using dynamic electronic polarization.

theory

The hydrogen atoms of standard solvents have a magnetic moment which is proportional to their spin. In the earth's magnetic field, they precess around this field at a frequency proportional to its modulus (called the Larmor frequency, 1 to 3 Khz in the earth's field).

The resonant electromagnetic excitation creates by spin phase coherence a macroscopic magnetization component precessing at the Larmor frequency. This component induces a voltage in the detection coil. The measured frequency gives the value of the field.

The nuclear magnetism is not directly detectable in the earth's field. The dynamic electronic polarization amplifies by a factor of 1000 the nuclear signal. The nuclear spins are coupled to the free electron spins of a radical in solution.

Two excitation frequencies of the electronic resonance are possible: one gives a positive polarization, the other negative. The frequencies depend upon the solvent used.

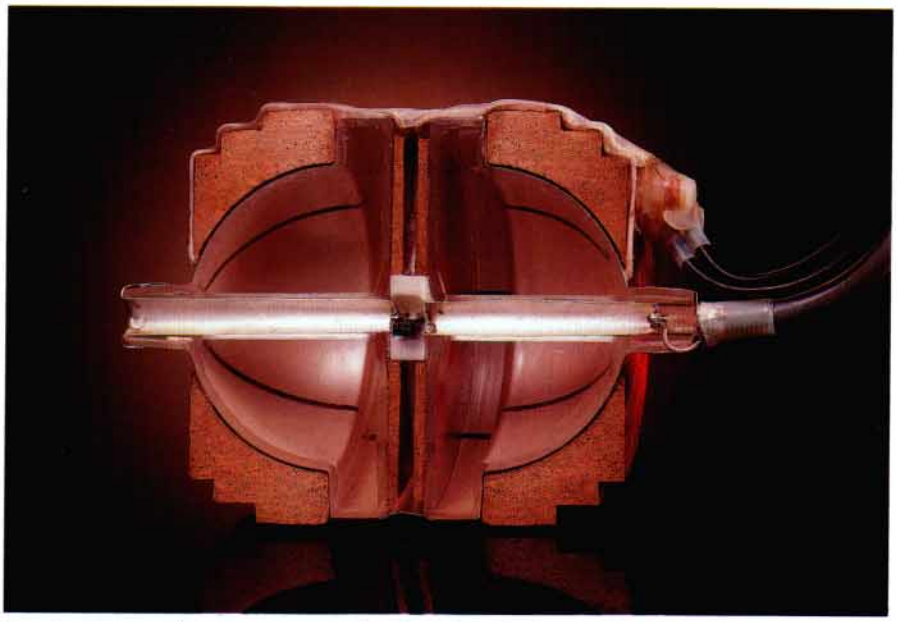
The correct choice of a pair of solvents containing the same radical will give, at the same frequency, a positive polarization factor in one and a negative one in the other (double effect).

probe description

The probe is composed of:

- two hydrogenated solvents in individual flasks containing a free radical in solution;
- a high frequency dynamic polarization excitation circuit;
- a low frequency circuit which simultaneously excites the nuclear resonance, and measures the signal. It is constructed of two symmetrical coils mounted in opposition.

The "double effect" allows the detector to be connected as an oscillator with the associated electronics: the differential amplifier connected to the low frequency circuit rejects the excitation signal and amplifies



Nuclear magnetic resonance probe (section view)

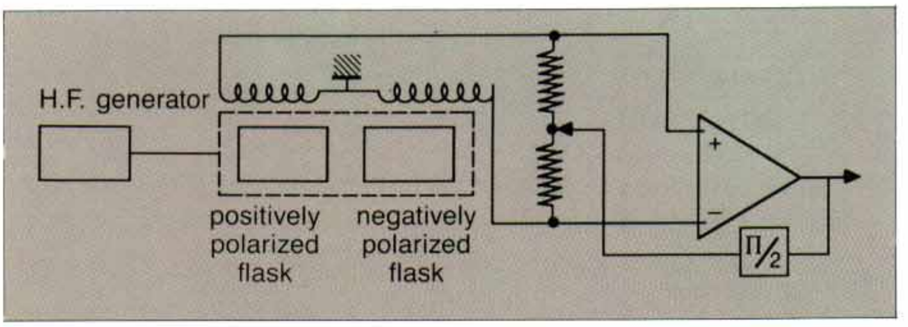


Diagram of N.M.R. probe oscillator

the detected voltages of the opposite signs: the signal is re-injected in common mode.

This configuration has the advantage of eliminating external electro-magnetic noise detected in a symmetrical manner by the coils.

The isotropy of the probe with respect to the field direction is obtained in frequency and amplitude by:

■ its conception: spherical form, electrical connections, revolution symmetry;

■ the choice of components selected for their amagnetism.

(Tests carried out using a SQUID magnetometer developed by D LETI).

The free-radical solutions are stable (> 15 years).

industrial development

This probe is manufactured by the company CROUZET (Valence).

technical specification

• sensitivity	10 pT. $Hz^{-1/2}$
• band-width	10^{-4} to 10^{-1}Hz
• field range	20 to 70 μT
• output frequency	1 to 3 kHz
• anisotropy	100 pT
• consumption	2 W
• warm-up time	3 s
• working temperature range	−40 to +70°C
• weight	3,4 kg
• volume	1,3 dm^3
• mean time between failures	6500 hours
• no maintenance	

applications

The magnetometer is made up of the probe, an amplifier and a precision frequency meter.

The principal applications of this detector are: the measurement of weak magnetic fields and the detection of magnetic objects. Its stability enables it to be used in hostile environments (airborne detection, underwater detection).

■ **military applications:**
Anti-submarine warfare (this probe is carried aboard the "Breguet Atlantique" aircraft of the french navy).

■ **civil applications:**
Oil and mineral prospection, archeological research, volcanic surveillance and the detection of magnetic objects buried or immersed (search for the TITANIC).

D LETI uses the trade mark GAMCIS in this domain.

■ **space applications:**
A project to send an N.M.R. magnetometer into space is being considered. This apparatus would be used to study the earth's magnetic field.

The company CROUZET is the only licensee for space and military applications.

PATENT:
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