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Suppression of magnetic noise in the fundamental-mode orthogonal fluxgate

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Abstract

A new important advantage has been discovered for the fundamental-mode operation of the orthogonal fluxgate employing an amorphous wire. It has been found that a great enough dc bias practically completely suppresses the magnetic noise generated in the fluxgate core by the ac-bias field; the fluxgate resolution becomes limited only by the excess electric noise in the ac-bias current. As a result, the magnetometer resolution increases by a factor of 60 and reaches 10 pT/$\sqrt{\text{Hz}}$ at frequencies above 2 Hz. The suppression of magnetic noise can be explained by excluding magnetization reversals in the fluxgate core. In the fundamental mode, the fluxgate core is kept saturated continuously due to the unipolar bias, and magnetization varies by coherent rotation. Practically no magnetic noise is generated in this case. In the second-harmonic mode, magnetization is reversed by the bipolar bias. This causes nucleating domains and generating intensive magnetic noise in the fluxgate core.

Keywords: ac bias; dc bias; Fundamental mode; Noise suppression; Offset; Orthogonal fluxgate; Second-harmonic mode

1. Introduction

Fluxgate magnetometers are currently one of the best choices for industrial and field applications, where precise unshielded measurements should be performed at relatively high, non-cryogenic temperatures [1–4].

The fluxgates are miniature (their active area can be as small as a few cubic millimeters), robust, inexpensive, and precise. Commercially available fluxgates provide a 100 pT/$\sqrt{\text{Hz}}$ resolution and 10 nT absolute precision [1]. The state-of-the art fluxgates provide a 10 pT/$\sqrt{\text{Hz}}$ resolution, 1 nT long-term stability, and 0.1 nT/°C thermal drift [1,2].

Compared to unshielded high-temperature superconducting quantum interference devices (SQUIDs), fluxgates may have a similar noise level, but their measurement range is much wider [1,2].

There are two main types of fluxgate magnetometers [5–7]: a *parallel* one, where both the measured and excitation fields have the same direction, and an *orthogonal* one, where the excitation field is perpendicular to the magnetometer axis.

Conventional *orthogonal* fluxgates are described in [6–11]. The simplest of them [9–11] consist of a single magnetic core and a single pick-up coil. The excitation electric current is applied directly to the core. The main advantages of these fluxgates are their simplicity and small size compared to parallel fluxgates: a conventional parallel fluxgate is usually built by a differential scheme and employs either two separate cores or a single ring core. It also employs an excitation coil, which is absent in the simplest orthogonal fluxgates.

Conventional low-noise fluxgates, either parallel or orthogonal, are usually operated in *second-harmonic* mode [5]: the fluxgate core is excited with a periodic bipolar magnetic field and the output signal is detected at a frequency that is twice the excitation one. Some other conventional modes of operation are also used [5], however they do not provide low-noise performance.

The main disadvantage of conventional *orthogonal* fluxgates operated in *second-harmonic mode* is their inferior noise performance compared to parallel fluxgates [5].

In this work we have revealed—for the first time to the best of our knowledge—that the inferior noise performance of conventional orthogonal fluxgates is caused by the second-harmonic mode of operation, and it can be dramati-

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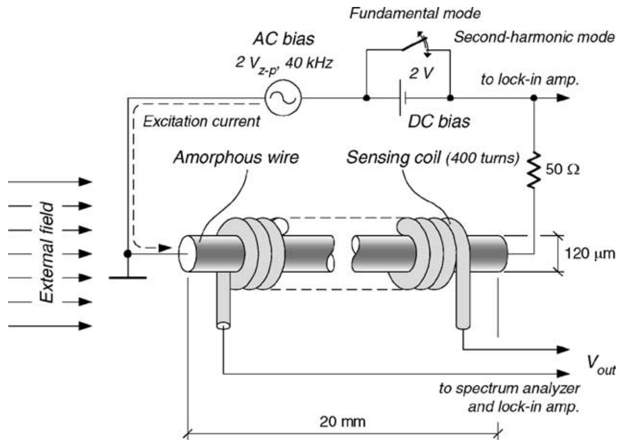

Fig. 1. Orthogonal fluxgate employing an amorphous wire.

cally improved due to the new mode of operation suggested in [12].

It is recently suggested in [12] to turn the bipolar excitation of the orthogonal fluxgate core (an amorphous wire) into a unipolar one by adding a dc component to the ac-bias current (see Fig. 1). With this new operating mode, the ac-bias fundamental, rather than the second harmonic, carries information on the external axial field [12].

The proposed in [12] *fundamental mode* doubles the fluxgate sensitivity and—what is more important—allows one to drastically reduce the fluxgate's offset. The latter is achieved in [13] due to the flipping of the fluxgate transfer characteristic with changing the dc-bias polarity.

In this work, a further important advantage is discovered for the fundamental-mode operation. It is found that a great enough dc bias practically completely suppresses magnetic noise generated in the fluxgate core by the ac-bias field; the fluxgate resolution becomes limited only by the excess electric noise in the ac-bias current. As a result, the magnetometer resolution increases by a factor of 60 and reaches $10\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$ at frequencies above 2 Hz.

Achieving in this work a tens of pico-tesla resolution along with the possibility of eliminating offset [13] paves the way for the constructing of low-cost miniature magnetometers for precise detection of weak magnetic fields in a wide frequency band.

2. Experiments and discussions

2.1. Experimental setup

The experimental setup includes an orthogonal fluxgate (see Fig. 1), two DS345 function generators, SR760 FFT spectrum analyzer, SR830 DSP lock-in amplifier, Agilent 54622D digital oscilloscope, and a magnetic shield with an 1000 shielding factor.

The fluxgate was fabricated with a Co-based amorphous wire (AC-20 type made by Unitica) of a 120 μm diameter and 20 mm length. The sensing coil was wound directly on the fluxgate core with a 50 μm copper wire and consists of 400 turns. The fluxgate was placed in the magnetic shield. The external field was applied along the fluxgate core with a calibrated solenoid. The bias currents, both dc and ac, were applied with the function generator.

2.2. Magnetic noise suppression

Our main aim was to investigate whether the fundamental-mode operation suggested in [12] has an effect on the fluxgate resolution, compared to the resolution achieved with the same fluxgate in the conventional, second-harmonic mode [9–11].

To reach this aim, we first investigated the dependence of the fluxgate noise on the dc-bias magnitude: we measured spectrum of the voltage generated in the sensing coil for different magnitudes of the dc bias, while keeping the ac bias at a fixed amplitude of 40 mA (see Fig. 2(a)). The ac-bias frequency was set at 40 kHz. At this frequency, the chosen ac-bias intensity corresponds to the nearly maximum sensitivity of the fluxgate in both the fundamental and second-harmonic modes: 1.1 and 0.6 μV/nT, correspondingly. The external magnetic field was not applied.

We have found in this experiment that the intensive noise ($>100\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$) observed at the fluxgate output for

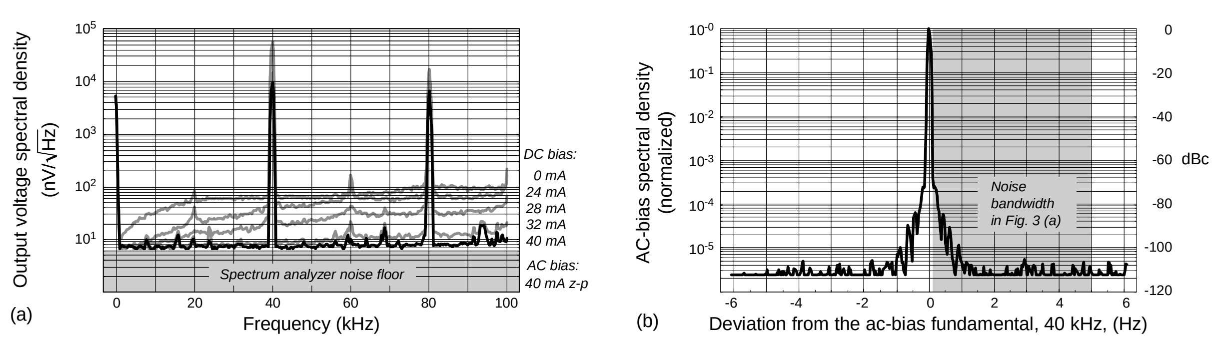

Fig. 2. (a) Comparison between the output signal voltage spectra obtained for different dc bias currents. A 40 mA dc bias corresponds to a purely unipolar excitation of the fluxgate core (fundamental mode) and a zero dc bias corresponds to a purely bipolar excitation (second-harmonic mode). (b) Normalized ac-bias spectrum (BMH window).

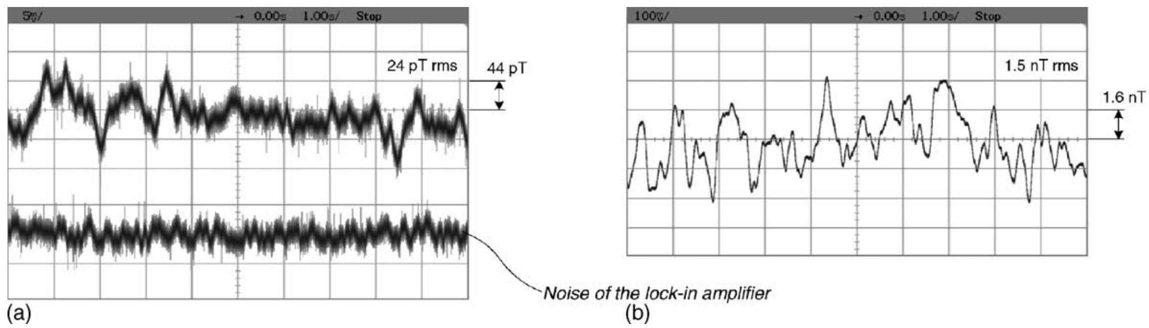

Fig. 3. Comparison between the sensitivity thresholds in the fundamental and second-harmonic modes: (a) with a 40 mA dc bias and the lock-in amplifier synchronized with the fundamental, (b) without dc bias and the lock-in amplifier synchronized with the second harmonic. Detecting bandwidth is 0.1–5 Hz.

the second-harmonic mode (with a zero dc bias) is drastically decreasing with increasing the dc-bias magnitude. This noise disappears almost completely—not considering the excess noise near the harmonics—just before the fluxgate excitation becomes unipolar. For a 40 mA dc bias, the residual noise floor is nearly equal to the input noise of the spectrum analyzer (6 nV/$\sqrt{\text{Hz}}$).

Secondly, we investigated the threshold of the fluxgate sensitivity—the smallest external field that can still be detected (we actually regard it as the resolution).

We detected with the lock-in amplifier the voltage noise generated in the sensing coil for a zero external field (see Fig. 3). The lock-in amplifier time constant was set at 30 ms, which corresponds to a 5 Hz bandwidth. The lowest noise frequency was 0.1 Hz due to the limiting of the signal recording time by 10 s. Thus, the measurements were done in a 4.9 Hz frequency range.

The lock-in amplifier sensitivity was set at 10 mV, and the amplifier's 10 V output range was expanded by a factor of 100, which correspond to a 10^5 gain. The offset in the lock-in amplifier output was compensated. The lock-in amplifier was synchronized either with the fundamental or with the second harmonic, depending on the operating mode investigated.

We have found in this experiment that the sensitivity threshold, 23.5 pT rms, measured in the fundamental mode is by a factor of 60 better than that (1.5 nT rms) measured in the second-harmonic mode.

As a result, a 0.1 nT zero-to-peak (z–p) external field can quite easily be detected in the first case (see Fig. 4(a)) compared to a 5 nT z–p field in the second case (see Fig. 4(b)).

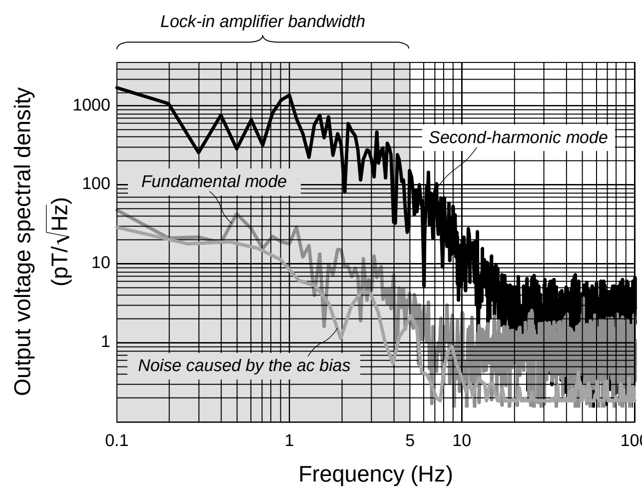

Fig. 5. Noise spectrum of the fundamental-mode orthogonal fluxgate as compared to the noise of the same fluxgate operated in the second-harmonic mode and to the noise part that is caused by the ac bias.

In Fig. 5 we compare in frequency domain the fluxgate noise signals shown in Fig. 3(a) and (b).

2.3. Fluxgate noise origin

Our next aim was to reveal the fluxgate noise origin. To reach this aim, we first compared in Fig. 3(a) the total

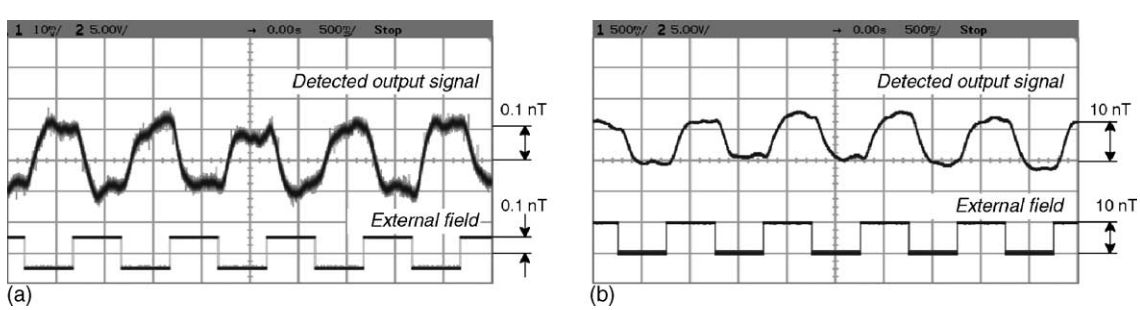

Fig. 4. Comparison between the detected output signals. The lower traces represent a 1 Hz external longitudinal field. The upper traces are obtained (a) with a 40 mA dc bias and the lock-in amplifier synchronized with a 40 kHz fundamental and (b) without dc bias and the lock-in amplifier synchronized with the 80 kHz second harmonic.

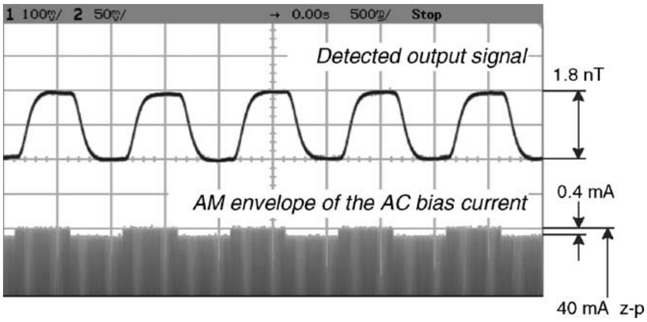

Fig. 6. Measurement of the output signal sensitivity to the ac-bias modulation in the fundamental-mode. DC bias is of a 40 mA magnitude. AC-bias amplitude is modulated with a square-wave signal. The modulation depth is 1% and the modulation frequency is 1 Hz.

fluxgate noise against the noise of the lock-in amplifier. One can see from this figure that relatively high-frequency components are nearly equal in the both signals, and the increase in the total fluxgate noise is due to a low-frequency component. In the fluxgate voltage spectrum (see Fig. 2(a)) this low-frequency component is represented by the excess noise near the fundamental and harmonics.

Thus, our task was to investigate the origin of the above excess noise: whether it was of purely magnetic nature and was generated within the fluxgate core, or it was a translation of the ac-bias noise (see Fig. 2(b)).

In order to estimate the contribution of the ac-bias noise to the fluxgate output, we measured first the sensitivity of the fluxgate output to the ac-bias current: the envelop of the ac-bias current was modulated with a 0.4 mA peak-to-peak, 1 Hz square-wave, and the fluxgate output was detected with the lock-in amplifier (see Fig. 6). The sensitivity was found to be of a 4.5 nT/mA value.

We then measured the excess electric noise in the ac-bias current near the fundamental (see Fig. 2(b)) in the same, 0.1–5 Hz, bandwidth as that of the fluxgate noise in Fig. 3(a). The ac-bias noise was of a 4.2 μA rms magnitude; hence, its translation to the fluxgate output was: 4.2 μA rms $\times$ 4.5 nT/mA $=$ 19 pT rms.

In order to compare between the total fluxgate noise generated in the fundamental mode and the translation of the ac-bias noise to the fluxgate output, we plotted the latter in Fig. 5. The comparison given in Fig. 5 reveals that the fluxgate noise is almost exclusively caused by the excess electric noise in the ac-excitation current.

We conclude, therefore, that in the fundamental mode practically no magnetic noise is generated within the fluxgate core.

2.4. Spectral purity

Our final aim was to investigate the spectral purity of the fluxgate output in the fundamental and second-harmonic modes. The results of this experiment are shown in Fig. 7 for a zero external field.

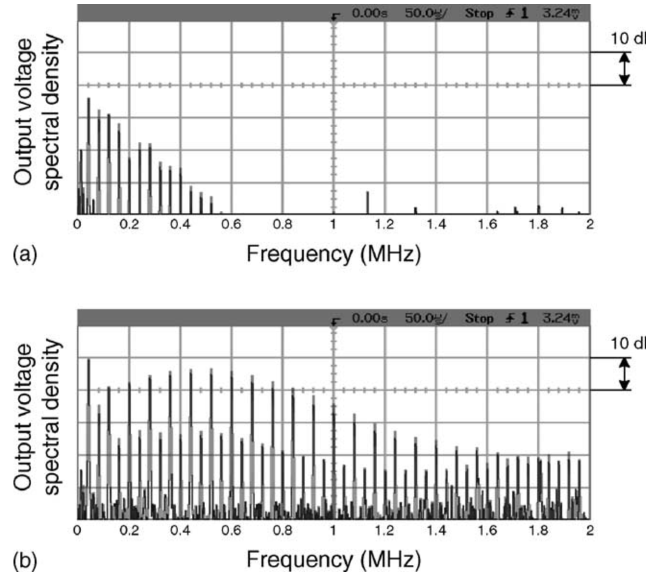

Fig. 7. Comparison between the fluxgate output spectra in (a) the fundamental and (b) second-harmonic modes.

Fig. 7 reveals an additional advantage of the fundamental mode. The bandwidth of the fluxgate response in this mode only by about a decade exceeds the ac-bias frequency. In the second-harmonic mode, the bandwidth of the fluxgate response is much wider. This complicates antialias filtering while using digital signal processors for handling the fluxgate output.

3. Conclusions

A new important advantage has been discovered for the fundamental-mode operation of the orthogonal fluxgate employing an amorphous wire. It has been found that a great enough dc bias practically completely suppresses the magnetic noise generated in the fluxgate core by the ac-bias field. The fluxgate resolution becomes limited only by the excess electric noise in the ac-bias current. As a result, the magnetometer resolution increases by a factor of ~60 and reaches 10 pT/$\sqrt{\text{Hz}}$ at frequencies above 2 Hz. (The long-term stability measured in a tens of minutes range was within 1 nT.)

The suppression of magnetic noise can be explained by excluding the magnetization reversals in the fluxgate core. Fig. 8(a) illustrates that in the fundamental mode, the fluxgate core is kept continuously saturated due to the unipolar bias, and magnetization varies by coherent rotation. Practically no magnetic noise is generated in this case. Whereas in the second-harmonic mode (see Fig. 8(b)), magnetization is reversed by the bipolar bias. This causes nucleating domains in the fluxgate core and, consequently, generating an intensive magnetic noise.

Another advantage discovered for the fundamental mode is related to a much better spectral purity of the fluxgate output signal. This alleviates antialias filtering while using

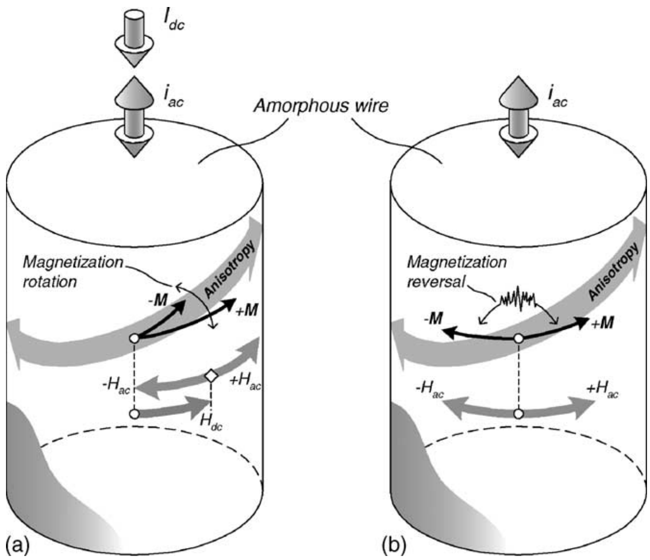

Fig. 8. Magnetization behavior in the (a) fundamental and (b) second-harmonic modes.

digital signal processors for handling the fluxgate output signal.

Achieving a tens of pico-tesla resolution along with the possibility of eliminating offset [13] paves the way for the constructing of low-cost miniature magnetometers for precise detection of weak magnetic fields in a wide frequency band.

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References

[1] P. Ripka, Advances in fluxgate sensors, Sens. Actuators A 106 (2003) 8–14.
[2] D. Robbes, C. Dolabdjan, Y. Monfort, Performances and place of magnetometers based on amorphous wires compared to conventional magnetometers, J. Magn. Magn. Mater. 249 (2002) 393–397.
[3] P. Ripka, New directions in fluxgate sensors, J. Magn. Magn. Mater. 215/216 (2000) 735–739.
[4] R.S. Popovic, J.A. Flanagan, P.A. Besse, The future of magnetic sensors, Sens. Actuators A 56 (2000) 39–55.
[5] P. Ripka, Review of fluxgate sensors, Sens. Actuators A 33 (1992) 129–141.
[6] F. Primdahl, The fluxgate magnetometer, J. Phys. E: Sci. Instrum. 12 (1979) 241–253.
[7] D.I. Gordon, R.E. Brown, Recent advances in fluxgate magnetometry, IEEE Trans. Magn. 8 (1972) 76–82.
[8] E.H. Frei, S. Shtrikman, D. Treves, A transducer using crossed fields, Bull. Res. Counc. Israel 3 (1954) 443.
[9] T.M. Palmer, A small sensitive magnetometer, in: Proceedings of the IEE, 100 pt. II, London, 1953, pp. 545–550.
[10] L.R. Alldredge, Magnetometer, US Patent 2 856 581 (1958).
[11] F. Primdahl, The fluxgate mechanism, IEEE Trans. Magn. 6 (1970) 376–382.
[12] I. Sasada, Orthogonal fluxgate mechanism operated with dc biased excitation, J. Appl. Phys. 91 (10) (2002) 7789–7791.
[13] I. Sasada, Symmetric response obtained with an orthogonal fluxgate operated in fundamental mode, IEEE Trans. Magn. 38 (5) (2002) 3377–3379.

Biographies

Eugene Paperno received his BSc and MSc in Electrical Engineering from the Minsk Institute of Radio Engineering, Minsk, Republic of Belarus in 1983. From 1983 till 1991, he was with the Laboratory of Optical Methods for Information Processing, the Institute of Electronics, Belorussian Academy of Sciences. In 1992, he joined the Department of Electrical and Computer Engineering, the Ben-Gurion University of the Negev, Israel and in 1997 obtained his PhD Summa cum laude, which was a study of magnetoresistive sensors applications in magnetometry. After 2 years as a JSPS Post-Doctoral Fellow with the Department of Applied Science for Electronics and Materials, Kyushu University, Japan, he returned to the Ben-Gurion University of the Negev, Israel and is now a Staff Member of the Electrical and Computer Engineering Department, Head of the Instrumentation, Circuits and Devices Track, and Head of the Analog Design Laboratory. His current interests are magnetic tracking systems for human computer interface and virtual reality systems, magnetic shielding, magnetometry, electronic, magnetic, and optoelectronic instrumentation.