Diode Lasers

Biomagnetic Measurements Benefit from Laser Know-How

Atom magnetometers enable precise magnetic field measurements of the human heart and brain

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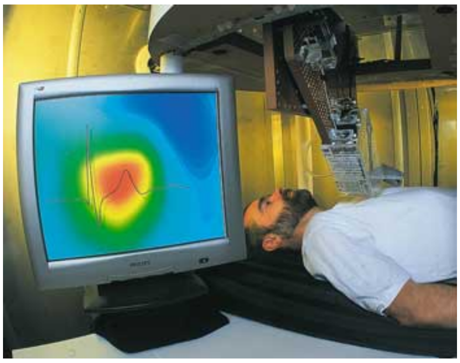

Fig. 1: Magnetocardiography – the assessment of the magnetic field of the human heart – permits an early diagnosis of heart diseases. (The University of Fribourg apparatus, courtesy of Swiss National Science Foundation)

Monitoring the electric currents of the human heart and brain has long become clinical routine. An electrocardiogram (ECG, the measurement of the electric potential of the heart muscle) helps to detect cardiovascular diseases and guides therapy thereof. Similarly, the electroencephalogram (EEG, monitoring of brain currents) is an indispensable tool in the treatment of epileptic patients. Unfortunately, both methods have their limits: Not every infarct is identified in an ECG, and the EEG fails to precisely localize the brain currents.

Magnetocardiograms (MCG) and magnetoencephalograms (MEG) – measurements of the current-induced magnetic fields – are more sensitive methods to detect the onset of pathological changes than their electric counterparts. However, widespread use of these techniques has been hampered by the cost and inconvenience of the instrumentation available. New laser-based methods demonstrated by researchers at the Universities of Fribourg (Switzerland) and Princeton (USA) provide a cheap and compact alternative: Atom magnetometers rely on precision measurements in atomic physics and latest diode laser technology.

Magnetic fields of heart and brain

The most prominent magnetic field within the human body is generated by the heart. More precisely, every heartbeat is triggered

by an electric pulse that spreads through the heart muscle. This process corresponds to a weak electric current – the source of the heart’s magnetic field. Its amplitude is rather weak: it peaks at 100 Picotesla (pT), about a million times weaker than the Earth’s magnetic field (50 µT), and three to six orders of magnitude less than typical stray fields of railways, cars or elevators.
Neuronal processes in the human brain give rise to a complex, ever-varying electromagnetic field, and neuroscientists have come to believe that this field plays a crucial role in the functioning of the brain, synchronizing and coordinating the processes that create it. The magnetic field of these processes is still smaller than that of the heart: Whilst brain waves of a person daydreaming correspond to an amplitude of 70 Femtotesla (fT), the usual level of brain activity creates a field in the 10 fT range.
Field strengths that weak call for elaborate detection techniques. Baule and McFee, who discovered the heart’s magnetic field back in 1963 [1], used a large-scale induction coil. Since the 1970s, so-called SQUIDs (Superconducting Quantum Interference Devices) have become the “gold standard” in magnetometry. Whilst commercial SQUIDs reach impressive sensitivities down to $3\ fT/Hz^{1/2}$, their operation requires cooling with liquid helium (4 K) or liquid nitrogen (77 K). This makes the operation of these devices costly and cumbersome, and has hampered widespread acceptance of magnetocardiography and -encephalography.

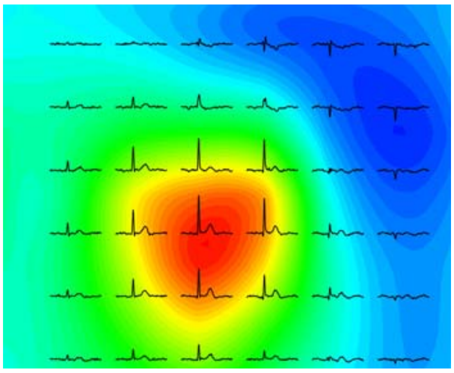

Fig. 2: Magnetocardiogram of a healthy volunteer. The map shows the peak amplitude of the magnetic field as a function of position above the chest. The top right corner of the map corresponds to the data point closest to the left shoulder. In the red areas, the field points into the chest, while in the blue areas, the field vector points outwards. The field structure resembles that of a current dipole inside the chest. (Courtesy of A. Weis and G. Bison, Fribourg)

Atomic spin magnetometers

The concept of an atom magnetometer is based on measuring the precession of electron spins in a magnetic field. The Larmor frequency, at which the spins rotate about the field axis, is directly proportional to the field strength.
At the Université de Fribourg, a research team lead by Antoine Weis and Georg Bison used cesium (Cs) atoms to map the magnetic field of the human heart [2]. Their sensors comprise a small volume (6 cm^3) of Cs vapor, which is optically pumped with circularly polarized light from a TOPTICA 895 nm diode laser (DL 100). The researchers were able to record two-dimensional magnetocardiograms by stepping their sensor across the chest (Fig. 1). A gradient magnetometer further reduces the influence of external stray fields: One sensor is placed next to the chest detecting both the heart’s field as well as magnetic noise of the environment. A second sensor, further away, only measures the stray fields. Subtracting the two signals yields the field amplitude of

the heart (Fig. 2) with an impressive sensitivity of < 500 fT/Hz$^{1/2}$. Weis and Bison are confident that their MCGs will help to detect pathological changes in the heart and its function at an earlier stage than a standard ECG does. A major advantage of the Cs magnetometer is that it operates at room temperature, reducing equipment size and operating costs as compared to SQUIDs. Bison hopes that his technology will become sufficiently mature for marketing in less than two years.

Michael Romalis and co-workers at Princeton University harnessed potassium (K) atoms to build a magnetometer capable of measuring the magnetic field of the human brain (Fig. 3). Their experiment is wrapped up in several layers of µ-metal magnetic shields, reducing the influence of external stray fields by no less than six orders of magnitude. To boost their sensitivity into the Femtotesla range, Romalis needed to counter a phenomenon known as spin-exchange relaxation: When two polarized K atoms collide, their spins can flip and rotate in the wrong direction, causing loss of signal. The researchers realized that they could suppress this process, paradoxically, by increasing the vapor density and rate of collisions: if the atoms collide fast enough, the spins just do not have time to decohere between collisions [3]. The Princeton team coined the name SERF – a spin-exchange relaxation-free process – for their technique.

In a SERF magnetometer, a single sensor reaches a level of 7 fT/Hz$^{1/2}$, limited only by thermal currents flowing in the magnetic shields. A differential measurement, similar to the method of Weis and Bison, helps to reduce some of this noise and achieves a sensitivity of 0.5 fT/Hz$^{1/2}$, which is likely the most sensitive measurement of a magnetic field to-date. Measurements of brain activity are now under way, and the researchers hope to get new insights particularly into basic functions such as touch and vision that reside in the periphery of the brain.

The Princeton experiment, too, employs diode laser technology from TOPTICA, in this case a DL DFB tuned to the K D_1 resonance at 770 nm.

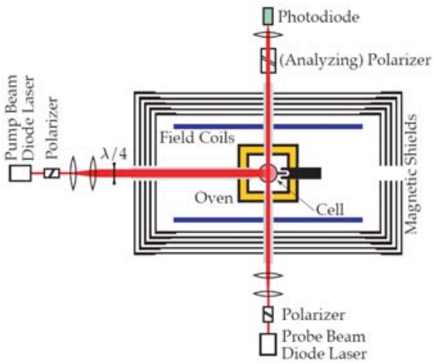

Fig. 3: Sketch of the Potassium magnetometer. Placed within several layers of magnetic shielding, the Potassium sample is heated and optically pumped by a circularly polarized laser beam (“pump beam”). Thereby, the spins of the unpaired electrons align in the direction of polarization (z). Placing a sample with a small magnetic field at right angles to the spin direction tilts the spins into the x/y plane. This orthogonal polarization is interrogated with a linearly polarized probe laser beam, which is focussed onto a linear array of photo diodes. (Courtesy of Tom Kornack, Princeton)

Diode lasers of the next generation

DL DFB lasers (Fig. 4) are the systems of choice for the forthcoming clinical evaluation. The built-in DFB (distributed feedback) diode comprises a frequency-selective grating within the active region of the semiconductor, which restricts the laser

emission to a single longitudinal mode. Using novel metalization techniques on the preprocessed epiwafer, new DFB wavelengths can be manufactured even in small volumes and at affordable costs, removing one of the big roadblocks of the past.
Compared to alternative concepts with external gratings or mirrors, this monolithic setup greatly reduces the acoustic sensitivity of the laser. The laser performance does not suffer from unwanted mode hops, even in case of changing ambient conditions. The emission frequency can be conveniently stabilized to an atomic transition, and stable, unattended laser locks over periods of several weeks can easily be realized with modules like the new DigiLock 110 or FALC 110 (Fig. 5). Integrated opto-mechanical assemblies with fiber coupling, semiconductor amplifiers and intelligent laser driver concepts complement TOPTICA's portfolio of DFB-based laser solutions for this application.

Fig. 4: DL DFB lasers with low noise control electronics are used in today's most precise magnetometers.

Future challenges

The potential of laser-based biomagnetic diagnostics is unquestioned. Next steps might be the miniaturization of the gas cell, the optical components, and the detector circuitry. Also, an MCG is still composed of a series of individual measurements, recorded in a scanning fashion across the chest. An array of sensors could map different regions simultaneously and shorten examination times.
First steps towards a miniature magnetometer have been taken by John Kitching's group at NIST, Boulder [4]. Their battery-operated sensor employs a Rubidium vapor cell with a size of a rice grain (3 x 2 x 1 mm) and achieves a sensitivity below 100 fT, enough to detect the magnetic waves of a mouse heart.
With a portable magnetometer at hand, the scope of applications becomes broader yet, extending even outside the realm of medicine. Anything that causes magnetic field anomalies can be localized and detected: deposits of iron in geophysical surveys, buried objects in archaeological sites, shipwrecks, and potentially even bombs or shells hidden in luggage.
The laser is, and will be, a central component of any atom interferometer, and its reliability is of major importance as the devices make their move from physics labs to the outside world. Single-mode DL DFB lasers have been successfully used by leading groups in the field and are ready to stand the challenge.

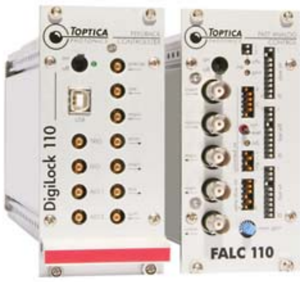

Fig. 5: DigiLock 110 and FALC 110: modules for linewidth narrowing.

References

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