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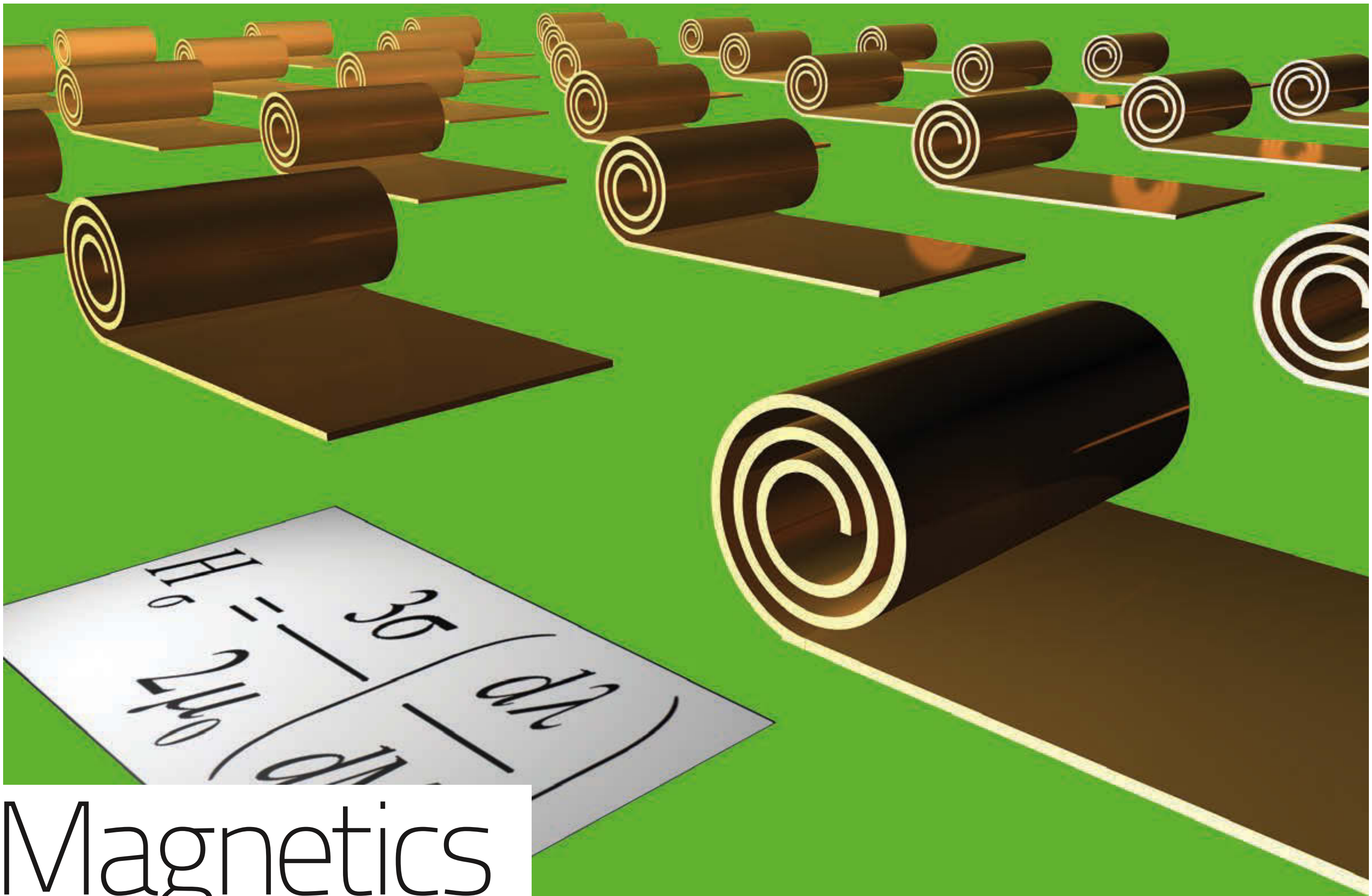
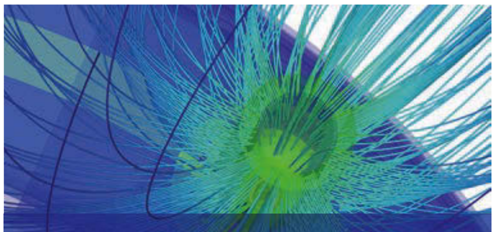
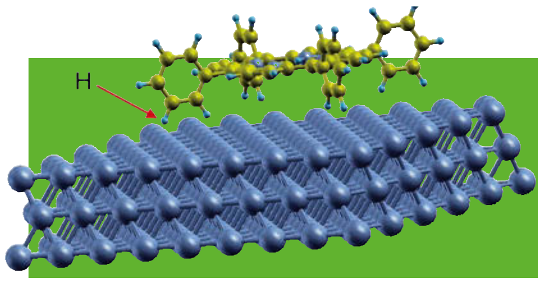


Magnetics with a **twist**

Researchers at the University of New Orleans have pioneered a way to realize highly sophisticated 3D functional magnetic micro- and nanostructures to be formed by bending and twisting flat film patterns



How accurate electromagnetic simulation is enabling coils and permanent magnets to be designed, modeled and fully optimized



Scientists at the Nebraska Center for Materials and Nanoscience advance condensed-matter and electronic-structure calculations

THE WORLD'S LEADING GLOBAL REVIEW DEDICATED TO SHOWCASING THE LATEST DEVELOPMENTS IN ADVANCED MAGNETICS AND MAGNETIZED PRODUCTS

Phillip Keller, Metrolab

Measuring magnetic **field transients**

New devices based on 19th century technology are helping engineers measure low-level and short-lived parasitic effects such as eddy currents

Nature abhors sudden changes to a magnetic field. Not only does a coil's self-inductance resist changing the driving current, eddy currents also produce a magnetic field that opposes the primary one. And yet, certain applications require exactly such rapid field changes; examples include the gradient coils in an MRI scanner or switching magnets for directing particle beams. Yet how do engineers quantify low-level and short-lived parasitic effects such as eddy currents? A new generation of magnetometers addresses precisely this technical challenge.

Fluxmeters: resolution and bandwidth

Somewhat surprisingly, the new and high-tech magnetometer in question is actually a fluxmeter, a 19th century device based on basic physics (Figure 1). This technique is still commonly used in industrial as well as research applications.

Compared to the ubiquitous Hall magnetometer, fluxmeters can achieve much greater resolution (on the order of 10^{-5}), primarily due to the averaging performed by the integrator. In addition, fluxmeters provide a differential measurement, ignoring even the strongest offset field and focusing entirely on transients. Compared to other high-resolution magnetometers, particularly NMR, fluxmeters are much more flexible (for example, for inhomogeneous fields or the flux density within a material) and feature much greater bandwidth (tens of kHz instead of tens of Hz).

On the other hand, fluxmeters require a carefully constructed and calibrated coil, are very sensitive to temperature variations, and suffer from drift, for example due to the thermocouple effect of bimetallic contacts. In short, fluxmeters demand thought and impeccable technique in exchange for flexibility, resolution and bandwidth.

Industry versus research applications

Over the years, the magnetics industry has developed a number of standard fluxmeter applications. Sophisticated techniques and specialized coils have been developed to measure magnetic flux, flux density, field strength, magnetic potential, or the magnetic dipole, in a variety of magnetic circuits (Figure 2).[1]

A number of manufacturers produce voltage integrators for these industrial applications. At their core, one generally finds an analog electronic

Figure 1 (right and below right): **The flip-coil and the ballistic galvanometer, a classic fluxmeter. Images courtesy of the Historical Scientific Instrument Gallery, Department of Physics, University of Nebraska**

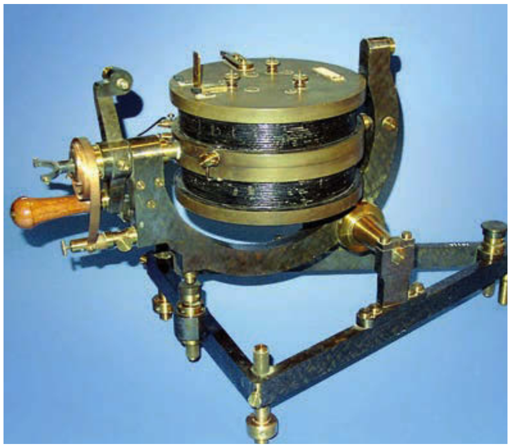


Figure 2 (left and below): **An example of a modern-day industrial fluxmeter, with a Helmholtz coil to measure the magnetic dipole of permanent magnets. Images courtesy of Magnet-Physik Dr SteinGroever, Cologne, Germany**

integration circuit, yielding basically similar performance (Table 1).

In contrast, only one significant research application uses fluxmeters: it is the standard technique used by accelerator physics laboratories such as the CERN in Switzerland to characterize the magnets that steer and focus a particle beam (Figure 3).

The instrument shown in Figure 3 dominated the research niche for more than 25 years. Developed at CERN and industrialized by Metrolab, the Precision Digital Integrator (PDI) featured a radically new architecture and provided significant performance improvements over an analog integrator (Table 1). Though its high resolution and accuracy are both important to physicists, the key difference between the PDI and a typical industrial integrator is the high measurement rate, where the start and stop of each partial integral are precisely synchronized with, for example, the angular travel of a rotating coil.

Measuring transients: better resolutions

The timing requirements became even more stringent when the research community set to measuring not just the static characteristics of beam magnets, but also low-level dynamic effects (Figure 4).[3] CERN, in collaboration with the

Faraday's law of induction:

$$V = -\frac{d\Phi}{dt} \Rightarrow \Delta\Phi = -\int_{t_{start}}^{t_{end}} V\,dt$$

where V is the coil output voltage, Φ is magnetic flux, and [t_{start}, t_{end}] is the integration interval.
In terms of flux density:

$$\Phi = \int_S \vec{B}\cdot d\vec{a} \Rightarrow$$

$$\Delta B = \frac{\Delta\Phi}{A\cos\vartheta} = -\frac{1}{A\cos\vartheta}\int_{t_{start}}^{t_{end}} V\,dt$$

where B is flux density, S is the surface subtended by the coil, A is the coil's effective area and θ is the angle between the magnetic field and the coil axis.
The SI units for flux (Φ) are Webers, Wb = V×s, and for flux density (B), Tesla, T=V×s/m².

Above: **Faraday's law of induction is a basic law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force. It is the fundamental operating principle of transformers, inductors, and many types of electrical motors, generators and solenoids**

Table 1: **Key characteristics of voltage integrators used in industry and research**

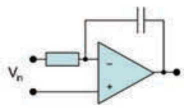
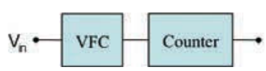
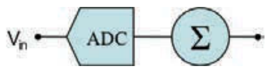
Parameter	Industry (typical)	PDI5025	FDI2056
Principle of operation			
Max. number of channels	1	2	3 (or more)
Resolution (μWb)	0.1	0.01	10^{-8}
Accuracy (%)	0.1	0.01	0.001
Drift (full scale/minute)	10^{-6}	10^{-4}	10^{-5}
Max. measurement rate (Hz)	25	1000	500,000
Max. input voltage (V)	± 60	± 5	± 100
Input impedance (kΩ)	100	10^3 or 10^6	200
Internal memory (samples)	1	2000	1,000,000
Computer interfaces	RS232, IEEE 488	RS232, IEEE 488	USB, Ethernet; industrial PC built-in

Figure 3: **Scale model of the setup used by physicists to characterize particle beam magnets. A long rotating coil measures the integrated field seen by the particle beam – which determines the kick – as a function of angle. The Fourier transform of these angular measurements yield the components relevant for the beam optics. For example, a dipole magnet, which steers the beam, generates a single sinusoidal period per coil rotation, whereas a quadrupole, which focuses/defocuses the beam, generates two periods. Real magnets, for example a quadrupole whose poles are not perfectly matched, generate some mix of these and higher-order components. Clockwise from the top: PDI5025 voltage integrator, rotating-coil jig with angular encoder, and the magnet under test**

University of Sannio in Italy, set out to develop a Fast Digital Integrator (FDI), with a measurement rate at least 100 times faster than the PDI. To compensate for the shorter integration interval, the resolution had to be improved in proportion – fortunately by refining the measurement of time, which is relatively easy, rather than voltage, which is relatively hard.

To achieve their goal, CERN and the University of Sannio made the decision to use an all-digital architecture, based on a high-performance ADC that had just become available. Once again, Metrolab decided to license the CERN design and commercialize an industrialized version, dubbed the FDI2056 (Table 1).

The future of fluxmeters

Compared to typical industrial fluxmeters, or even the PDI, the performance of the Fast Digital Integrator FDI2056 is in a league of its very own. So, does this mean that all previous voltage integrators have now become as obsolete as the ballistic galvanometer illustrated in Figure 1? Although some might like to think so, the answer is clearly ‘no’.

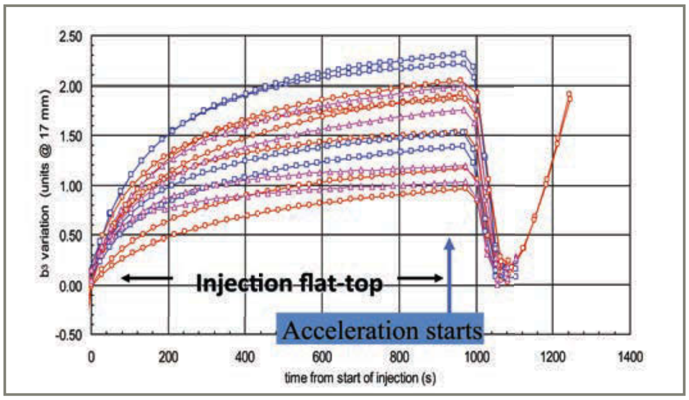


Figure 4: **The problem that motivated the development of a Fast Digital Integrator: the optics of the large dipole magnets for CERN’s LHC accelerator change dynamically, depending on how the magnet is ramped. Each data point requires a complete rotating-coil measurement; hence the need for speed. The effect is also on the order of 1 unit, which means 10^{-4} of the primary field (from Reference 2)**

Each instrument has its roots in a real-world application, with corresponding requirements. The vast majority of modern-day fluxmeters are used for industrial applications whose requirements are relatively stable, and certainly don’t require (and can’t afford) a quantum leap such as the FDI.

The FDI is also not everyone’s dream instrument. For example, it is interesting to note that the PDI and FDI have worse drift performance than industrial instruments (Table 1). For rotating coil applications, this is irrelevant, since the result at 0° should equal that at 360°, and the drift can be corrected after the fact. But this is not the case for most industrial applications.

Nonetheless, as described earlier, there are industrial applications that might very well benefit from such an instrument. For these applications, the FDI enables physicists and engineers to measure low-level, transient perturbations that were previously simply impossible to measure.

In the longer term, technological trends appear to favor digital integrators, and speed will be an incidental by-product. Today’s FDI2056 represents the shape of future fluxmeters. And the future remains bright for this 19th century technology. ■

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