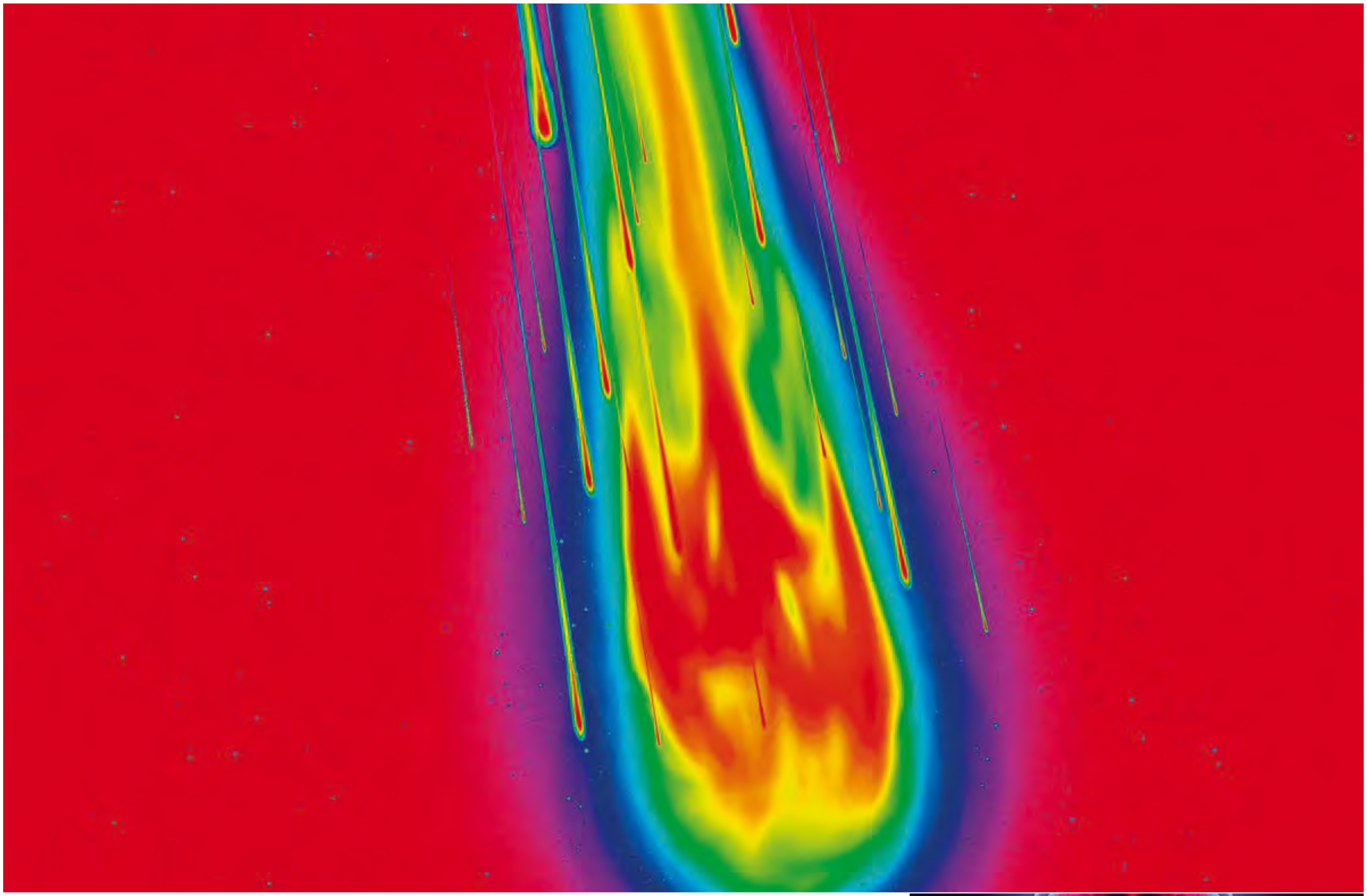
ANNUAL **2014**

MAGNETICS
TECHNOLOGY INTERNATIONAL



Meteoritic **legacy**

Advances in first-order reversal curve analysis of meteoritic metal are enabling Cambridge University scientists to reconstruct the all-important processes that formed the solar system

Researchers at Iowa State University are exploring new time-varying magnetic fields that can be used for the safe treatment of neurological disorders

An Imperial College London team reports on how a range of measurement breakthroughs is greatly benefiting the standardization of magnetic materials

The world's leading global review dedicated to advanced magnetics and magnet technologies

Philip Keller, Metrolab

Precision magnetic field **mapping**

New NMR magnetic field mapping systems address the evolving needs of magnet manufacturers in terms of field strength, resolution, spatial detail, bore size and cost

During the fabrication and installation of a magnetic resonance imaging (MRI) system, small inhomogeneities in the magnetic field are corrected by shimming, as outlined in Figure 1. As a consequence, an accurate field map is crucial to computing the exact compensation required. After shimming, the field is remapped to verify the results and then, if needed, the entire process is repeated.

The key element of the magnetic field mapper used by most manufacturers for this process is an NMR probe array (Figures 2 and 3). When the operator presses a button on a remote control, the probe array simultaneously measures up to 32 points on a plane. The operator then manually rotates the measurement plane by a fixed angle and the process is repeated until the entire surface of the defined spherical volume (DSV) has been mapped. This mapping process typically takes less than five minutes, minimizing errors due to drift or human error.

1

Figure 1: **The B_0 magnet in an MRI system is generally a 1.5T or 3T superconducting solenoid, large enough to accommodate a human. Iron shims and shim coils are used to compensate for field inhomogeneities, due either to coil imperfections or environmental disturbances (Photo courtesy of Philips)**

Higher fields, better resolution

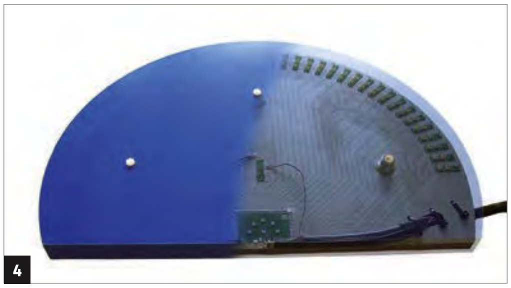
The NMR resonant frequency measured by an NMR magnetometer is exactly proportional to the magnetic field strength.[1] The proportionality constant is called the gyromagnetic ratio, γ. For water or the natural rubber samples usually employed in probe arrays, $\gamma \approx 42.6$MHz/T, and for deuterium (heavy water), $\gamma \approx 6.54$MHz/T.

Current-generation magnetic field cameras are limited to 7T, simply because they only go to 300HMz. Metrolab's new-generation NMR Precision Teslameter PT2026 offers a frequency range of up to 1GHz, thus pushing the maximum field with rubber samples to over 23T, and with deuterium samples to a hugely impressive – and entirely theoretical – 153T. A probe array based on the PT2026 (see Figure 4, next page) has already been built to map an experimental 11.7T whole-body MRI system. The full range of 23T is perfectly suited for mapping, for example, NMR spectroscopy magnets.

In addition, whereas today's systems use a continuous-wave (CW) technique to detect the NMR resonance – i.e. to sweep the RF frequency and detect an absorption peak – the PT2026 also supports pulsed-wave (PW) detection, by irradiating the sample with a broadband pulse and analyzing the re-emitted frequencies. The latter technique avoids all issues related to synchronizing sweep with detection; combined with low noise and advanced signal processing, it results in <1Hz resolution in stable, homogeneous fields. For strong fields, this approaches one part per billion. Magnet manufacturers have therefore welcomed this improved resolution, as measuring the field decay rate of a new superconducting magnet now takes less time, which means a gain in productivity.

2

Figure 2: **The magnetic field camera consists of an array of NMR probes (blue) mounted on a rotating jig. The jig's vertical supports are bolted to the magnet's cryostat, and the rotation is performed manually using a disk**



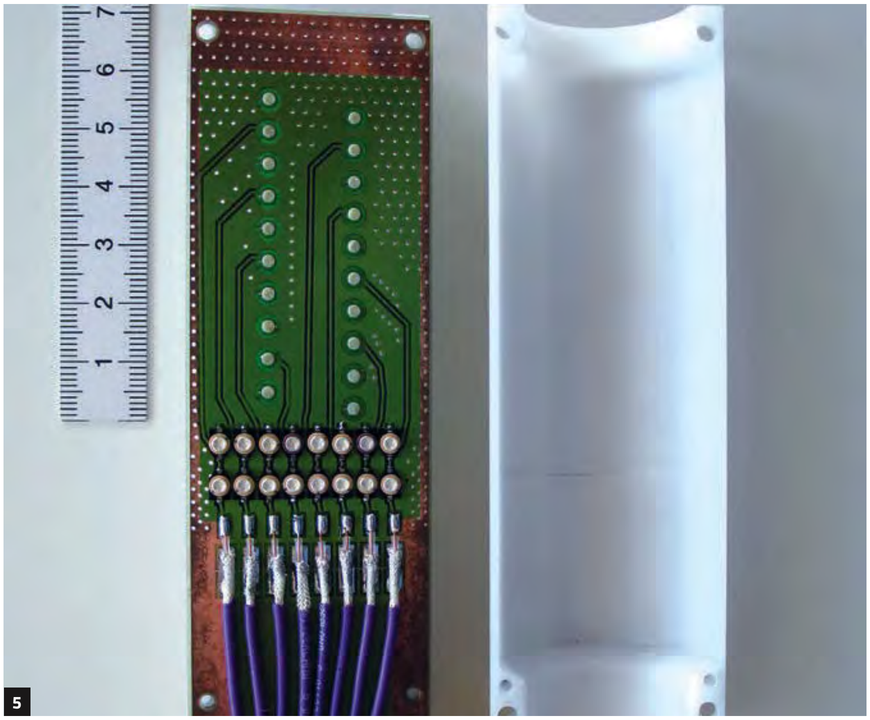


Figure 3: **The current generation of NMR probe arrays can map fields from 0.2-7T, with up to 32 points arranged on a semicircle 160-500mm in diameter**

Figure 4: **Probe array for the 11.7T full-body MRI scanner being developed by the joint French-German Iseult project.[2] It features 40 measurement points at 500MHz on a 475mm diameter semicircle, plus a wide-range probe in the middle. The RF switches at the bottom are the only active components; unlike current-generation probe arrays, each measurement point requires just a coil and two trim caps**

Figure 5: **Experimental probe array for 300MHz (7T) and 400MHz (9.4T) vertical small-bore NMR spectroscopy magnets. The 16 active probes are arranged on a 13.2mm x 37.5mm rectangle, interleaved left and right to maximize their vertical spacing. Dummy probes at the top and bottom of each row minimize inconsistencies due to paramagnetic effects. Generating a map with 32 angular positions takes less than five minutes**

More points, smaller bores, lower costs

Although they look similar, the new-generation PW NMR probe arrays are fundamentally different from their CW predecessors. The PW probes are pulsed one after the other and processed sequentially, whereas the CW probes are excited continuously and therefore must be processed in parallel. The sequential operation theoretically removes all constraints on the number of channels. Although practical constraints due to RF switch performance remain, probe arrays with hundreds of channels are now within the realms of possibility.

Another key difference is that a PW measurement head is much less complex than its CW predecessor. The corresponding size reduction permits building very compact probe arrays (Figure 5), thus addressing the needs of manufacturers of small-bore magnets used in animal MRI, NMR spectroscopy and general physics.

Before starting the shimming process, a superconducting magnet is ramped up to its nominal field by injecting current. This process must be carefully monitored to avoid overshooting and to minimize the chances of an accidental quench. Traditionally, this requires a second NMR magnetometer with a single large-range probe. Once the magnet reaches its nominal field strength, the large-range probe can be removed and the probe array installed. If the magnet happens to quench at this point – not an uncommon occurrence during manufacturing – the entire process must be repeated.

Thanks to the sequential processing of PW probes, and the general flexibility of the PT2026 architecture, a large-range probe can now be integrated into the probe array (Figure 4). Thus two instruments are combined into one, minimizing the manufacturer's investment costs, and especially operational costs due to equipment setup.

Next-generation probe arrays

Existing NMR probe arrays permit mapping a 500mm diameter volume, with a field resolution of better than 0.1 parts per million and spatial resolution of several 100µm, in a factory environment, within a matter of minutes – all of which is no easy feat.

Recent developments have enabled the creation of a new generation of probe arrays that extend the range from 7T to 23T; improve the maximum resolution by an order of magnitude; increase the maximum number of channels also by an order of magnitude; enable the mapping of small-bore magnets; and subsume the functionality of wide-range NMR magnetometers.

Despite such impressive inroads, there is still plenty left to be done in this field. Although the new probe arrays have been shown to work, they have not yet achieved the level of industrialization of their predecessors, and this will take time and patience. With hundreds of channels, one can now envision three-dimensional probe arrays, eliminating the need for a mechanical jig; however, cost-effective methods of building such structures still need to be invented. With the sequential processing of PW probes, one can also envision replacing the passive trim caps in all probe heads with varicaps, and adding switches for the tuning voltages. Such wide-range probe arrays address the needs of specialty manufacturers who build custom magnets or small series. And future PT2026 system improvements – for example improving tolerance to field inhomogeneity – will result in corresponding performance improvements for probe arrays. As such, it's safe to assume that the future of NMR precision field mappers is bright! ■

References

1. NMR Magnetometers, *Magnetics Technology International* (2011), p68-71
2. http://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=3058