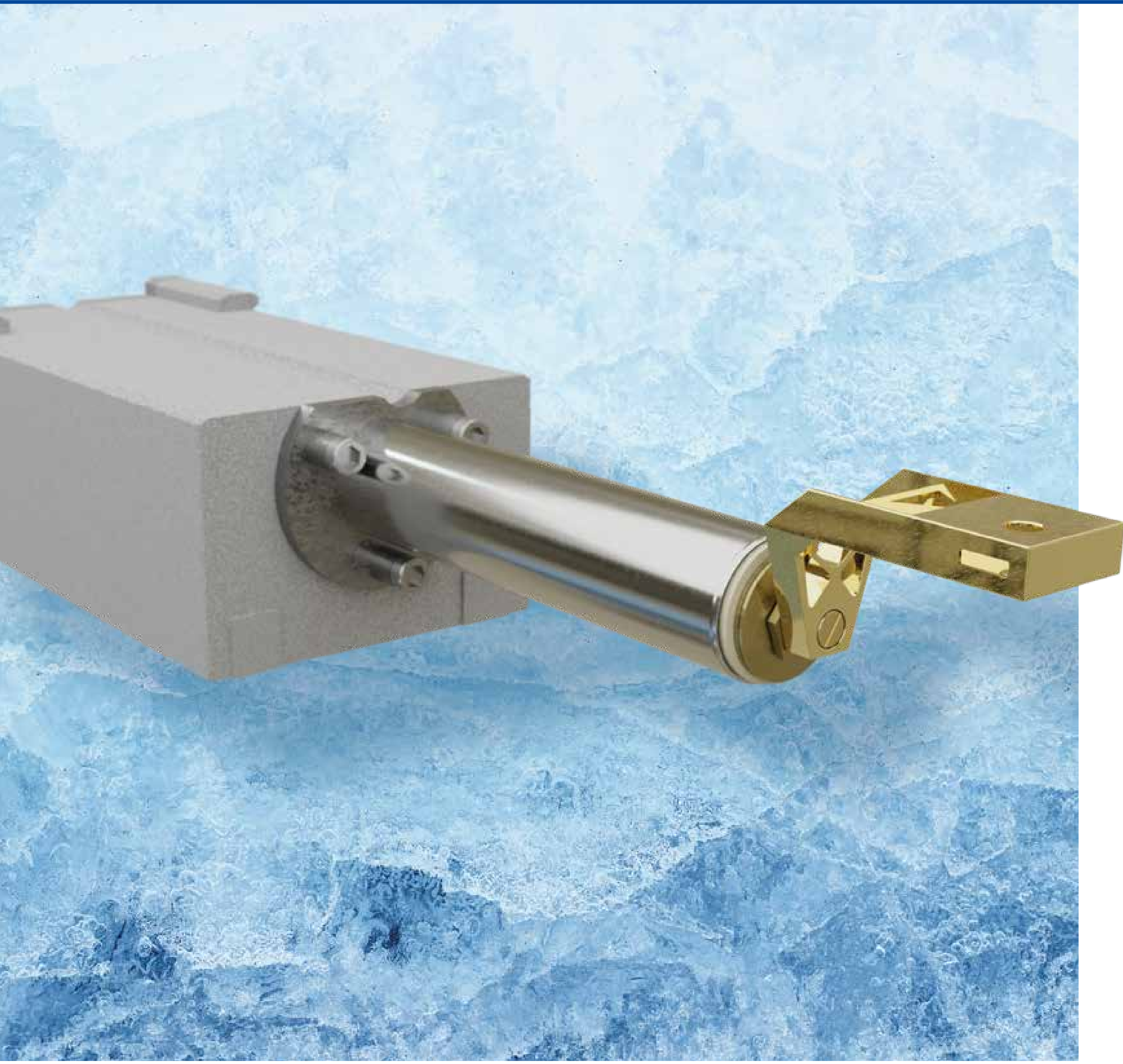
DSPE MIKRONIEK

2022 (VOL. 62) ISSUE 3

PROFESSIONAL JOURNAL ON PRECISION ENGINEERING



- THEME: COOLING & CRYOGENICS
- ZERO-VIBRATION COLD TIP FOR CRYOGENIC ELECTRON MICROSCOPY
- IN-LINE INTERFEROMETRY FOR PRECISION IN ROLL-TO-ROLL PRODUCTION
- WIM VAN DER HOEK'S DESIGN PRINCIPLE OF ENERGY MANAGEMENT

MIKRONIEK IS A PUBLICATION OF THE DUTCH SOCIETY FOR PRECISION ENGINEERING – WWW.DSPE.NL

PUBLICATION INFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics. The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

DSPE
YOUR PRECISION PORTAL

Publisher
DSPE
Julie van Stiphout
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

Subscription
Mikroniek is for DSPE members only.
DSPE membership is open to institutes, companies, self-employed professionals and private persons, and starts at € 80.00 (excl. VAT) per year.

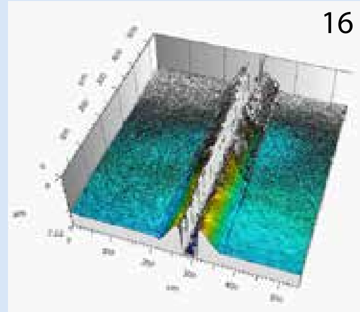
Mikroniek appears six times a year.

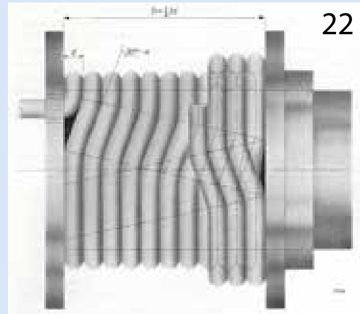
ISSN 0026-3699

The cover image (featuring a cryogenic micro-cooler) is courtesy of Demcon kryoz. Read the article on page 10 ff.

IN THIS ISSUE

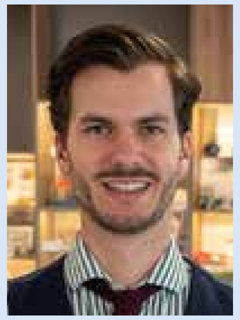
THEME: COOLING & CRYOGENICS


16


22

FEATURES

THE VALUE OF MEETING, COLLABORATING AND SHARING KNOWLEDGE IN FACING CURRENT CHALLENGES IN TECHNOLOGY



With common roots that go back more than 50 years, Mikrocentrum and DSPE recently intensified their collaboration. While collaborating many times over the years, for example on the yearly Precision Fair which is organised by Mikrocentrum, we both realised there are more common grounds. With both having a strong focus on knowledge sharing and networking, we decided to boost our collaboration by co-organising events. One of these new events is the Techcafé.

A Techcafé was born

As of January 2022, I am the new Mikrocentrum High Tech Platform manager. When starting this position, I soon got the opportunity to collaborate with DSPE and together we created the Techcafé. The concept is simple: it's an accessible event where you go for content, new contacts and inspiration. It's the place to discuss tech challenges and exchange best practices. All this is presented in a talk show setting with experts from science and industry. And afterwards we enjoy drinks and bites. The first edition of the Techcafé, on 28 April at our premises in Veldhoven (NL), focused on robotisation, and immediately whetted everyone's appetite for more.

Calling on SMEs

The room was packed and a vibrant discussion by Heico Sandee (founder of Smart Robotics), Mark Stappers (lecturer at Fontys University of Applied Science), Wouter Kuijpers (program officer at Eindhoven University of Technology) and Martin van der Have (sales & marketing manager at ABB) filled up the room. Their message was twofold: on the one hand, they noted that the introduction of industrial robots is still lagging behind considerably and that there are just as many obstacles surrounding this. Yet, at the same time they called on the SMEs present to make a start anyhow. The discussion didn't stay between these four experts, the crowd was also invited to participate and ask questions.

Next up: systems engineering

The enthusiasm for the first edition was so great that the second edition has already been scheduled. 7 July will be all about systems engineering, another typical high-tech theme. We will discuss design issues and their increasing complexity within the high-tech and manufacturing industry. This year, there's also an edition planned on 22 September and there's even a special edition on 16 November during the Precision Fair.

Ecosystem collaboration

The value of facing challenges as an ecosystem instead of one company on its own will become more and more important in the near future. Products are becoming more complex, have to operate faster, require more functions and have to become more and more sustainable and must have a lower carbon footprint. The same applies to the machines that have to make these products, which are also becoming more complex, larger and more critical. In addition, these machines must be delivered faster at a time when the global market is still upside down.

To face these challenges, collaboration is the way forward. This necessity is becoming increasingly clear to me and I'm proud that as the Mikrocentrum High Tech Platform manager, I have the opportunity to facilitate these collaborations and to connect people with each other, together with partners such as DSPE. Ultimately, working together is a lot easier if you already know each other or when you know where to find people who can help.

Maarten Roos
Manager Mikrocentrum High Tech Platform
m.roos@mikrocentrum.nl, www.mikrocentrum.nl

FROM BATHTUB TO REFRIGERATOR

The use of superconducting magnets for high-field Magnetic Resonance Imaging poses a big cooling challenge. Classic magnet cooling technology comes with operational and environmental issues, related to the venting and refilling of large quantities of helium. These issues are overcome by the Philips BlueSeal micro-cooling technology, which uses only seven litres of helium in a fully sealed system. This is just one step on the technology roadmap towards more patient- and environment-friendly MRI systems.

SHUBHARTHI SENGUPTA, MICHEL HAGENAAR AND MAARTEN DEKKER

MRI for hospitals

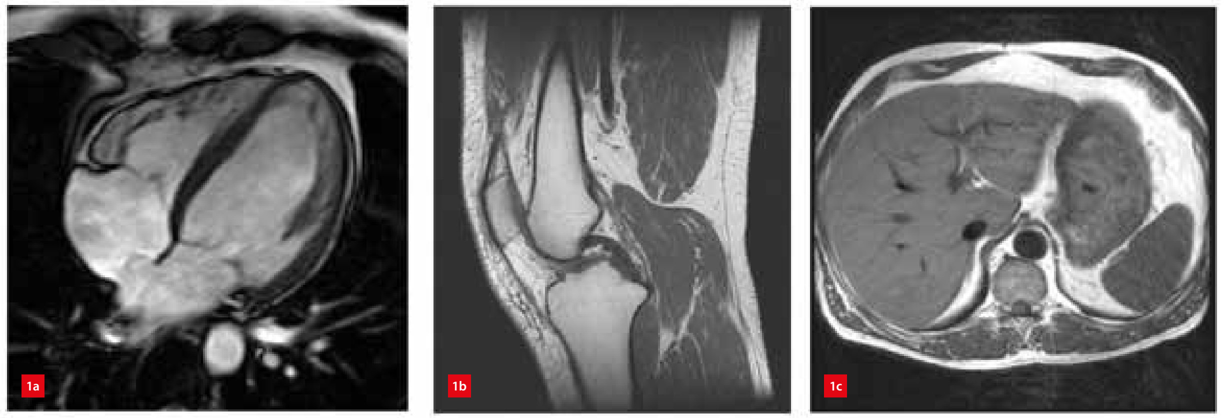
MRI, or Magnetic Resonance Imaging, is the preferred imaging modality when it comes to imaging soft tissues – such as the brain, liver, heart, among others – but also for imaging joints and blood vessels; see Figure 1 for a few examples. In contrast, CT, or Computed Tomography, scans are used for imaging fractures, tumours and cancer screening. In some cases, a patient may have a CT scan, followed by an MRI – with the images overlaid to determine abnormalities in pathologies.

Classic MRI technology

MRI is an imaging method based on the sensitivity to the presence and properties of water, which – incidentally – makes up between 70% and 90% of most tissues. The amount of water (or to be precise, mobile hydrogen atoms), and thereby its properties, can vary substantially with disease or injury, making MRI a sensitive and useful tool for patient diagnosis. MRI is able to detect the tiny perturbations in the magnetism of the nucleus – the entity at the centre of an atom.

Hydrogen happens to contain the simplest nucleus – a single, positively charged proton. Protons possess an inherent characteristic – spin. Atomic nuclei with an uneven number of protons will have a net spin, known as nuclear spin – as is the case with hydrogen ^{1}H, while nuclei with an even number of protons (and neutrons) do not have a net nuclear spin, like oxygen ^{16}O. This is in line with the Pauli Exclusion Principle – which posits that in an atomic nucleus, two identical particles cannot be in the same state [2,3].

In free space (without an external magnetic field), the spins are randomly oriented and their effects cancel each other. However, when these same spins are placed in an external magnetic field (such as that of an MR magnet), the spins align themselves parallel (spin up) or anti-parallel (spin down) to the magnetic field. The ratio of spin-up and spin-down states is not 1:1 – instead, there is a small number of excess spins (aligned parallel to the external magnetic field). These excess spins add up, resulting in a net magnetisation M. MR imaging exploits this net magnetisation M to generate images (Figure 2). Therefore, a well-designed

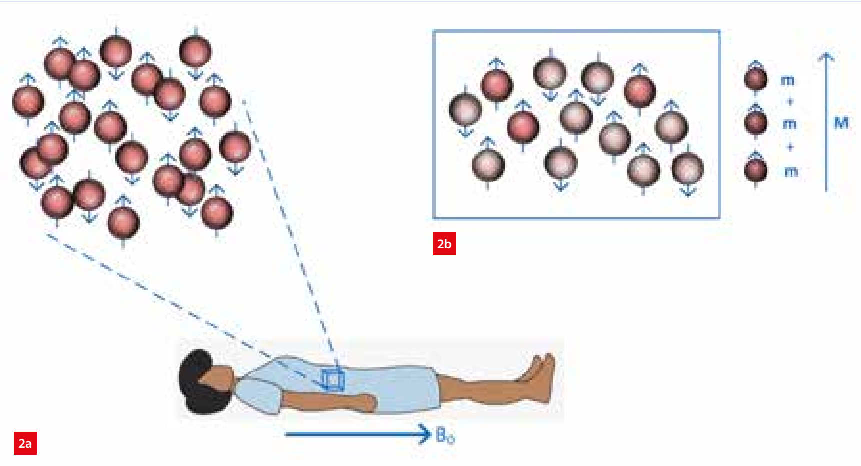


Magnetic Resonance Imaging applications [1].
(a) Cardiac imaging.
(b) Knee imaging.
(c) Liver imaging.

AUTHORS' NOTE

Shubharthi Sengupta (RF specialist and project leader), Michel Hagenaar (electronic hardware architect) and Maarten Dekker (group leader) all work in the Patient Centric Subsystems group at Philips MRI R&D in Best (NL).

maarten.dekker@philips.com
www.philips.com/mri



MRI's concept of net magnetisation.
(a) Alignment of spins in a small section of the body when subjected to an external magnetic field.
(b) The net vector sum of the spin-up and spin-down states results in a net magnetisation M.

The Philips MRI 5300 1.5T scanner.

magnet that is capable of producing a homogeneous B_0 field (or main magnetic field) is crucial for MRI.

But how do we go from spins to an MRI image? For this, see Figure 3. It requires the confluence of several different hardware and software solutions, working in perfect sync with each other. With the subject prepped for a scan, they are placed inside the bore such that the anatomy under investigation (brain, heart, knee, for example) is centred around the magnet isocentre (the area of the magnet with the most homogeneous B_0 field).

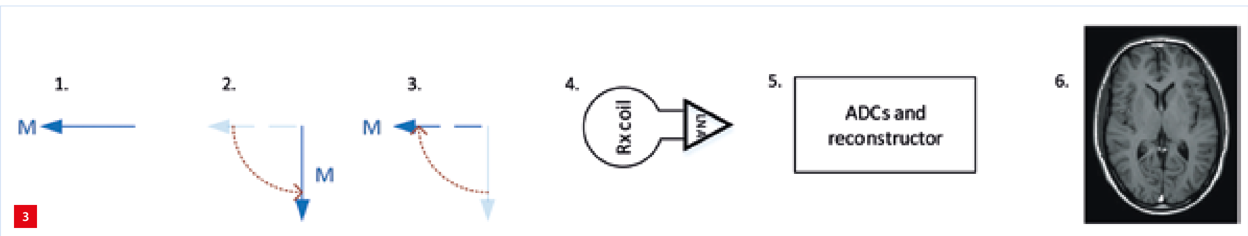
With the spins in the subject aligned along the main magnetic field, an instantaneous RF (radio-frequency) pulse (called a Transmit pulse, or B_1 field) generated using a transmit coil is made incident on the subject, orthogonal to the B_0 field. This flips the net magnetisation away from the B_0 field and into the plane transverse to the main magnetic field. Spatial localisation of the MR signal requires the use of three orthogonal linear magnetic field gradients – and these are generated by gradient coils mounted on a cylindrical former just inside the bore of the magnet.

Once the RF excitation plays out, the nuclei start releasing the absorbed energy and slowly move back in alignment with the B_0 field. A receive (Rx) coil, placed in close proximity to the subject, picks up this energy and produces an electrical signal across its terminals. This electrical signal is then fed into a low-noise amplifier that further amplifies the signal, upon which the resulting signal is routed to a signal processor (containing analog-digital convertors and other processing hardware) that helps form the final image [7].

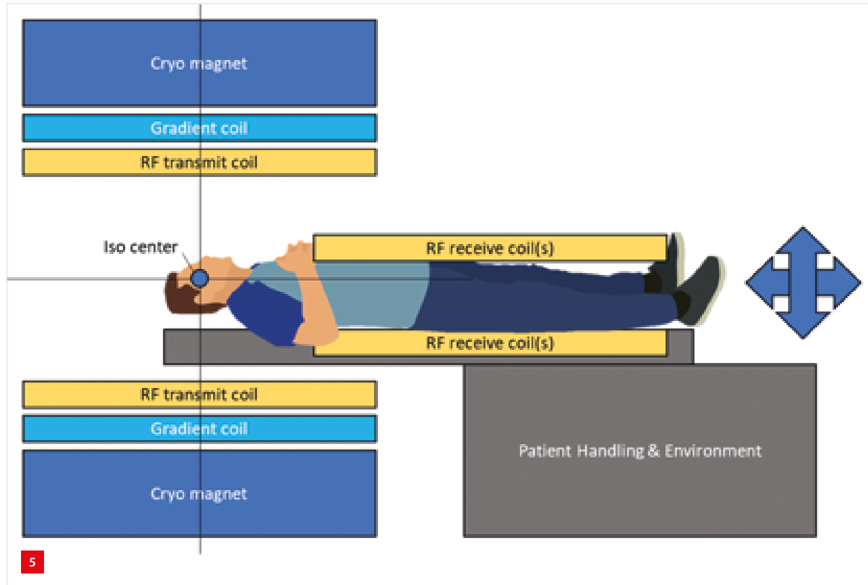
Figure 4 shows the Philips MRI 5300, a 1.5T scanner. A very basic hardware decomposition could be summarised as depicted in Figure 5.

MRI superconducting cryo magnet technology

While permanent and resistive magnets are capable of generating fields of up to 0.4 T, superconducting magnets are used for generating stable magnetic fields above 0.4 T [1]. Superconducting magnets use alloy wires (niobium-titanium, for example) cooled to ~4 K (–269 °C) using liquid helium, at which point they become superconducting. The conductor used in most clinical MRI scanners is



Going from spins to an MRI image.
(1) Net magnetisation M aligned with the main magnetic field.
(2) An orthogonal transmit pulse flips the magnetisation into the transverse plane.
(3) Excited spins now start moving back towards B0 and release energy.
(4) The released energy is picked up by a local receive coil, thus generating the MR signal.
(5) The amplified signal is fed into a reconstructor.
(6) The final MR image is generated.

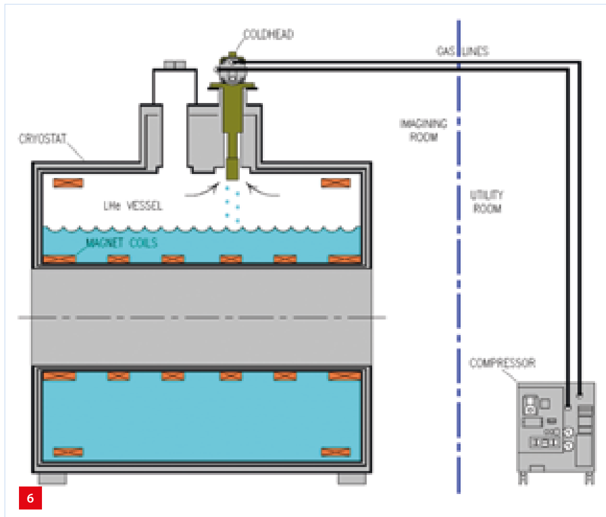


A very basic hardware system decomposition of an MRI machine.

niobium-titanium (NbTi), which becomes superconductive below 9.4 K.

The wires are composed of several microfilaments of NbTi embedded in a copper matrix – the copper not only provides support to the microfilaments, but also a low resistance path for large currents in the event of loss of superconductivity. Instead of a continuous winding, the coils are broken up into several windings, spaced apart, for increased B_0 field homogeneity [4]. The magnets also include additional shim coils (to improve B_0 field homogeneity) and active shielding coils, one at each end of the magnet (to minimise stray fields). The current direction in the active shielding coils is opposite to that in the main coils [5].

In order to enable the superconductivity in these coil windings, magnets employ a cryostat – a large chamber



Cut-out of a magnet showing the cryostat and superconductors.

filled with liquid helium (up to 1.500 ℓ, boiling point of 4.2 K) in which the magnet coils are immersed, surrounded by a further vacuum chamber (Figure 6). Early magnets added a further chamber of liquid nitrogen (at 77 K) to help reduce the continuous boil-off of the helium (due to external thermal energy entering the cryostat). Modern MRI magnets use cryogenic coolers to reduce or even eliminate helium boil-off, and thus do not require liquid nitrogen.

Compressed helium gas is circulated around a two-stage 'cold head' mounted on the magnet. Controlled gas expansion in this cold head is used to create very low temperatures at the two stages of the cold head. When the cooling cycle is completed, the helium gas is returned to a water-cooled compressor [1]. In older magnets, the two stages of the cold head were connected to two circumferential aluminium shields that intercept heat and thereby reduce the evaporation (boil-off) of the helium to a level of less than 50 mℓ/h. Later magnets have the first stage connected to a single shield, and the second stage connected to a recondensor so that helium reliquefies and cannot escape the magnet; see Figure 6. These latter magnets are referred to as 'zero-boil-off'.

Superconducting magnets are a costly proposition, and the use of cryogenic helium in such vast quantities results in an added expense – not to mention the environmental impact. Nonetheless, helium-cooled superconducting magnets are still the best option when it comes to generating stable, high magnetic fields for MRI.

Cooling innovation

Based on a decade of innovation, Philips BlueSeal (Figure 7) is a fully sealed magnet designed to simplify MRI installation, reduce lengthy and costly disruptions in MR services, and help hospitals transition to sustainable, helium-free operations. This revolutionary magnet operates with only 7 ℓ of liquid helium and is fully sealed [6].

Here, fully sealed refers to the fact that the helium used to transfer the dissipated energy to the second stage of the cold head is completely enclosed, without loss of helium for the lifetime of the magnet (leakage nor vaporisation). The cooling system does not require to be vented or refilled, even in an emergency event, since it is designed for the apparent pressure at room temperature.

The superconducting magnet coils are situated in vacuum to provide thermal isolation from the surroundings, and cooling channels are thermally connected to the coils. At the highest point of the system, a cold head is installed to exchange the heat. A self-generated heat flow sustains itself since the specific weight of helium increases at lower

LOW FORM FACTOR, HIGH STABILITY

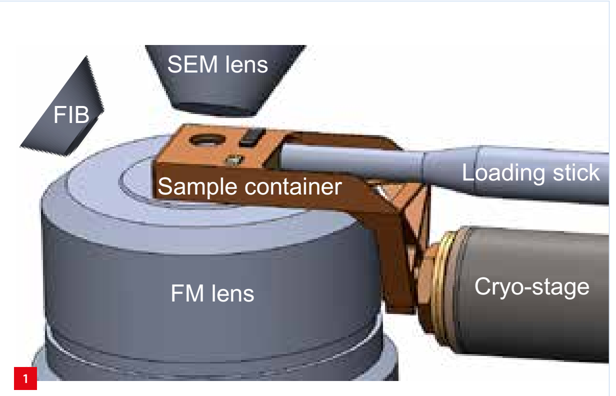
In life sciences research, cooling biological samples of, for example, proteins, viruses and bacteria to extremely low temperatures facilitates new forms of microscopy. This requires the integration of a sample holder provided with a cold stage into the workflow of preparing and analysing samples. Demcon kryoz designed an efficient cryogenic micro-cooler that has a low form factor and demonstrated its high mechanical and thermal stability.

PIETER LEROU

One of the upcoming techniques in life sciences research is CLEM (correlative light and electron microscopy), which combines light microscopy and electron microscopy. The two modalities are complementary to one another due to their different length scales: nanoscale electron microscopy provides high-resolution images of a sample while microscale light microscopy can be used for identifying regions of interest in the sample.

In a CLEM system, the sample is imaged using an electron beam and an optical light path simultaneously. This ensures that no changes have occurred in the sample during the analysis, as could be the case when the two microscopy modalities are used consecutively. Overlay of the two images is thus achieved automatically. Cooling to cryogenic temperatures is often used to fix (vitrify) the sample in order to obtain the highest resolution in imaging.

Delmic, located in Delft (NL), developed a fluorescence microscope (FM) that can be integrated with a scanning electronic microscope (SEM). If the SEM is additionally provided with a focused ion beam (FIB) for preparing samples before imaging, the resulting system comprises three 'lenses' centred around the sample (Figure 1). This restricts the available space for a sample holder fitted with cooling infrastructure. Nevertheless, it has to have high mechanical and thermal stability to achieve high-resolution imaging. As part of a joint development project, Demcon kryoz and Delmic collaborated to design and realise a cryo-FM/FIB/SEM using Demcon kryoz' novel cryogenic micro-cooler technology.



Schematic of a cryogenic sample holder for a microscopy system integrating three modalities: scanning electronic microscopy (SEM), fluorescence microscopy (FM) and focused ion beam (FIB).

AUTHOR'S NOTE

Pieter Lerou is CTO of Demcon kryoz, a full-service design house specialised in thermal systems engineering and located in Enschede (NL).

pieter.lerou@demcon.com
www.demcon.com/kryoz

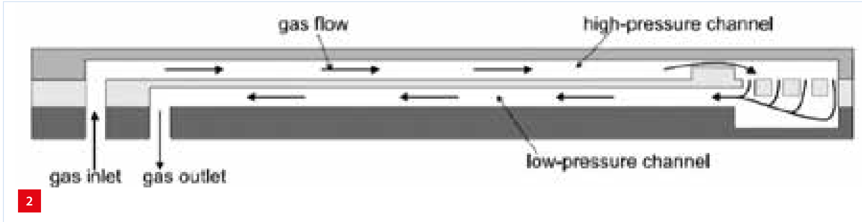
Design

Challenging requirements were defined for the cryogenic micro-cooler; see Table 1. Given the limited form factor and the long standing time, an efficient cooling solution was needed. For this, the Hampson-Linde cycle was selected, which is commonly used for the liquefaction of gases, in a regenerative cooling process that relies on the Joule-Thomson effect. Upon free expansion of a gas through a flow restriction, the gas cools and its temperature decreases. The advantage of this solution is that no compressor is required in the cooling device, i.e. there are no moving parts that can induce vibrations.

The actual implementation consists of a cooler chip that is made using lithographic techniques (Figure 2). Nitrogen gas is expanded from 95 to 1 bar, yielding a net cooling power of 200 mW at 80 K. No boiling liquid nitrogen is present in the system during operation, which keeps vibrations low. A sample holder is mounted on the cold stage, which in turn is integrated with cooling infrastructure (nitrogen high-pressure gas supply) into a complete micro-cooler. For manipulation of the sample, i.e. to position it with respect to either of the three 'lenses', the micro-cooler is mounted on a 5-DoF motion stage. Figure 3 shows the design of the micro-cooler and its mounting on an example stage.

Table 1
Main requirements for the cryogenic micro-cooler.

Sample temperature	≤ 108 K
Thermal stability	±20 mK (stationary)
Mechanical drift	≤ 4 nm/min
Vibration level (peak-to-peak)	≤ 1 nm @ 200 Hz
Degrees of freedom (DoFs)	5
Cool-down time	≤ 2 h
Standing time	> 6 h



The cold stage with the flow restriction on the right.

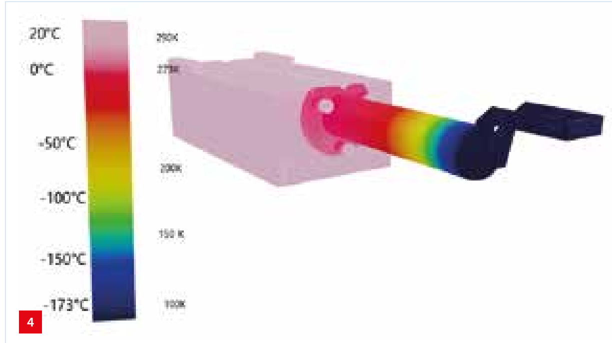
Thermal analysis of the complete system was performed using lumped-element modelling (LEM). Demcon kryoz has developed a dedicated LEM toolbox for use in the popular simulation environment Simulink, for modelling thermal, fluidic and vacuum systems to predict their (real-time) dynamic behaviour. It comes with a LEM library containing a large number of predefined modelling blocks that combine physical models with actual (off-the-shelf) part performance data, making detailed dynamic modelling of complex systems possible.

A schematic result of the LEM analysis is shown in Figure 5. It confirms that only the sample holder itself is cooled down to, for example, 100 K, while the cooler's base remains at room temperature. The large temperature gradient extends over a small distance (about 50 mm), which makes it possible to provide all mechanical interfaces to the cooler at room temperature, while the cryogenic temperature is only produced at the location where it is relevant, i.e on the sample.

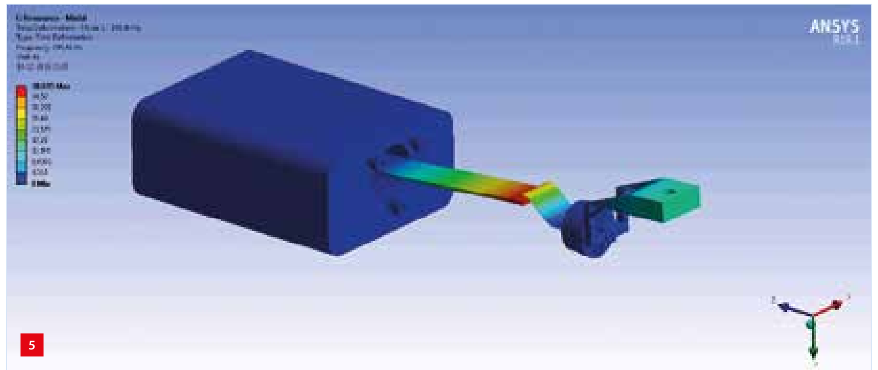
Verification

Testing of the mechanical and thermal performance was conducted at the Max Planck Institute of Molecular Physiology in Dortmund, Germany (Figure 6). The cryogenic micro-cooler was integrated in a dual-beam system, comprising a FIB for sample preparation and a SEM for analysis, while retro-fitted with an FM.

Peak-to-peak vibration levels for the cold tip (Figure 7) were found to be well below 1 nm over a wide frequency range up to 2 kHz, except for a peak at 50 Hz (probably a mains-related artefact). Hence, the requirement of ≤ 1 nm @ 200 Hz is amply met. Mechanical drift of the cold tip was measured to be below 3 nm/min, which satisfies the requirement of ≤ 4 nm/min. A duration test was performed to test the thermal stability (Figure 8), demonstrating the required ±20 mK, and the standing-time, for which 6 h was specified.



Result of thermal LEM analysis of the cryogenic micro-cooler design.



Modal analysis of the micro-cooler, showing the first mode and demonstrating the stability of the cold tip, of which the amplitude remains below 1 nm.

Design of the cryogenic micro-cooler. On the right, a still from an animation of the cooler mounted on a moving 5-DoF manipulation stage.