The magnet program of the High Field Magnet Laboratory at NCAS

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Abstract. The High Field Magnet Laboratory at the Radboud University in Nijmegen provides DC magnetic fields up to 33 T to a European-wide user community since May 2003. Starting from 2006 the HFML will be part of the Nijmegen Center for Advanced Spectroscopy (NCAS), a consortium focused on using a broad range of spectroscopic tools in high magnetic fields for nanoscience, and supported by the Innovation Platform of the Dutch Government. NCAS will develop a 45 T hybrid magnet system with 32 mm room temperature access in conjunction with a free electron laser, which will provide far-infrared electromagnetic waves in the range 100 μm – 1.5 mm (0.2 – 3 THz). In this contribution we will give an overview of the considerations for the hybrid magnet, and we will in particular list the options that are under discussion for the realization of the new hybrid magnet system.

1. Introduction

Modern science concentrates on finding techniques to make new materials and material systems with desired properties. These properties may be of technological relevance and/or have great scientific interest. Very advanced measuring facilities are necessary to reveal the properties of these new systems.

In the Netherlands many efforts have been dedicated to create facilities where novel materials are made. However, the advanced tools to measure and really demonstrate the new phenomena are often developed outside the Netherlands. It is therefore considered important to create an international centre for advanced spectroscopy with leading edge technology in advanced measuring facilities on one campus to maximize synergy.

At the Radboud University, the Nijmegen Centre for Advanced Spectroscopy (NCAS), a nearly 30 million Euro facility with international ambitions, has recently been funded by the Innovation Platform of the Dutch Government. NCAS aims to unify three already existing laboratories with newly proposed laboratories and instrumentation into a unique facility for high resolution spectroscopy of functional molecules and materials.

International facilities, such as Orsay, Grenoble, and Garching, show that the creation of a technocampus, combining top class experimental techniques, led by a core group of distinguished principal investigators, can lead to a centre of excellence attracting top class researchers and students from all over the world and catalyzing scientific and economic activity in the region.

Since the mid-seventies one of the focal points of the Institute for Molecules and Materials of the Radboud University Nijmegen has been the technological development and application of spectroscopy. With strong university support and significant outside funding, the High Field Magnet Laboratory (HFML) [1], the Nuclear Magnetic Resonance Laboratory (NMRL), the Trace Gas
Laboratory (TGL), and the NanoLab Nijmegen (a Nanoprobe Laboratory) have developed into world class spectroscopic facilities. NCAS implies a leap forward by joining these laboratories in a high-resolution spectroscopy facility and by founding a new High Resolution TeraHertz Free Electron Laser Laboratory and adding a 45 T hybrid magnet to the HFML, see Figure 1. The combined potential of these instruments and their physical proximity will provide high-field Electron Spin Resonance (ESR), up to 1.3 GHz Nuclear Magnetic Resonance spectroscopy, Scanning Probe Microscopy and Nano-spectroscopy.

![Figure 1. Research areas for FEL radiation and high magnetic fields.](image)

The NCAS will have a large impact on the structural and dynamic investigations of functional materials, large (bio-) molecules and tailor-made molecular assemblies with unprecedented resolution. The new infrastructure will be constructed around the HFML on the renewed Nijmegen Science campus and operated as an International User Facility for fundamental and applied science under the supervision of the Institute of Molecules and Materials, but will also independently offer unique capabilities.

The NCAS will consist of five parts:
1. The High Field Magnet Laboratory. The High Field Magnet Laboratory at the Radboud University in Nijmegen provides DC magnetic fields up to 33 T to a European-wide user community since May 2003. A new 50 mm bore 31 T resistive magnet will be made available to the users by the end of 2006, and a 30 T, 9 MW hybrid magnet will be operational by the end of 2007, offering a long term high magnetic field for e.g. NMR experiments. A new 45 T hybrid magnet will be constructed allowing the HFML to provide the limit of what is nowadays possible.
2. A high resolution THz free electron laser (THz-FEL). This instrument will be the focus of a new laboratory and will be designed and constructed offering radiation with a narrow band width in the far infrared/THz range for research both in combination with and without the high magnetic fields.
3. The Nuclear Magnetic Resonance Facility. In the future a high field (1 GHz) Nuclear Magnetic Resonance (NMR) Instrument will be developed and added to the existing NMR instruments. NMR experiments within high field magnets of the HFML permit even 1.3 GHz NMR and 2.0 GHz in the 45 T magnet at lower resolution.
4. The Trace Gas Facility. The laser laboratory facility will develop both continuously tunable, high resolution spectroscopy with high power, continuous wave, and Optical Parametric Oscillators down to 20 µm wavelength.
5. The NanoLab. This state of the art scanning probe laboratory will push the combination of THz and time-resolved spectroscopy with sub-wavelength, nanometer resolution and will pursue ESR and NMR with nanometer spatial resolution.

In the remainder of this contribution we will focus on the new 45 T hybrid to be designed and constructed for the NCAS project at HFML.
2. The 45 Tesla hybrid magnet: options and considerations

The combination of a superconducting magnet with a resistive magnet produces the highest possible continuous magnetic fields. However, this technology is extremely challenging and relatively expensive. HFML produces the highest continuous magnetic fields that are possible with purely resistive magnet technology (33 T-35 T). The extension with a hybrid 45 T magnet will mean a tremendous step forward.

The last decade has shown rapid advances in magnet technology. By the end of the 1990’s 33 T has become available resistively [2], and at the turn of the century 45 T became available in a hybrid magnet [3]. The ease of operation of a resistive magnet forms an important part of its attraction: simply pushing the ‘on’ button and turning the knob for the required field is sufficient. The electricity bill (power consumption of 20 MW at maximum magnetic field) is the only limit for the operation of resistive magnets.

On the other hand, hybrid magnets - the integration of a resistive magnet inside the bore of a superconducting magnet - produce significantly higher magnetic fields, but at the expense of a much more complicated operation. This is caused by the cryogenic requirements and the interaction between the superconducting and resistive parts. The cryogenic requirements are also an economical burden in exploitation because of the formidable liquid helium consumption and manpower needed. Therefore, hybrid magnets are not as widely used as are purely resistive or superconducting magnets, because of their sheer size and running cost, and also the high capital investment.

Recent technological advances in superconductivity (mainly high Tc superconductors, but also Nb₃Sn) and cryogenics have shown that it is possible to produce high performance Cryogen-Free (CF) superconducting magnets industrially [4], and the integration of CF superconducting magnets in a hybrid magnet has been demonstrated by a research laboratory [5]. Such a system removes the need for expensive cryogens, makes operation much simpler and cheaper, and reduces the capital investment for the superconducting magnet. Expertise in using conductive cooling is available at the IMR (Tohoku University, Sendai), the University of Twente and at several commercial companies (e.g. Jastec, Oxford Instruments, Cryogenic Limited and others).

Concurrently, a 35 T Series-Connected (SC) hybrid magnet is presently being constructed in Tallahassee [6]. This technology removes in part the troublesome interaction between the superconducting and the resistive part, since both are energized with the same source, which significantly reduces the running costs. A further advantage is that only a single power converter is needed, and the magnetic field is temporally very stable and suitable for high-resolution NMR and ESR experiments. The cable-in-conduit technology used for the outsert is well developed and there is relevant expertise at NHMFL in Tallahassee FL.

The combination of a Cryogen-Free and a Series-Connected Hybrid, a Series-Connected Cryogen-Free hybrid magnet (SCCF), would truly be an “at the flick of a switch” operated magnet, not only producing a much higher magnetic field than any of its constituents, but also combining all the advantages of its elements, notably higher stability at much lower running costs than a comparable resistive magnet because both the electricity bill and the liquid helium consumption are greatly reduced.

A SCCF hybrid magnet will offer significantly added value, both technologically and scientifically, over the simple sum of all the components, and at affordable running costs.

A conventional 45T hybrid is operational in Tallahassee [3], and indeed shows all the complications of hybrid magnets mentioned before. The magnet laboratory in Grenoble is still commissioning their hybrid magnet [7]. A SCCF hybrid magnet which would be part of the NCAS is taking advantage of the most modern developments and is expected not to suffer from the problems others experience with earlier technology.

But, cryogen free cooling has not yet been applied to a magnet system of the size and strength ambitioned. There are several problems that need to be addressed, e.g. the type of superconducting wire: for a SC outsert we need superconducting wire that can support large operating current (20 kA or more) for which cable in conduit is excellently suited, but cable in conduit cannot be used for a CF outsert. Issues as cooling down time (also after a quench of the outsert) will also play a role for systems larger than those that recently have been constructed.
3. Magnet Design and Construction

HFML possesses a 20 MW DC power converter which will act as a source for the insert coils or eventually in the case of a SC hybrid for both the insert and outsert. In order to achieve 45 Tesla a superconducting magnet with a bore of 500 mm to 600 mm and a central field of 14 T to 12 T is needed.

The resistive insert will be of the Florida-Bitter type, tailored to produce 33 T – 31 T using 20 MW, with the use of CuAg conductor where needed. Preliminary optimization shows that five subcoils will be needed to obtain the required insert field.

One of the challenges of a SCCF hybrid magnet lies in the fact that although a liquid helium operated 14 T superconducting outsert with a 600 mm bore already exists, a similar CF version still lies ahead: a central field of 15 T in 170 mm bore and 11 T in a 360 mm bore have been constructed both by industry and research laboratories and seems reliably operational. However, CF technology advances very quickly, and within two years we may expect that whatever is possible now with cryogens will also be possible using CF technology [5].

A 32 mm, <20 MW, 31 T insert to a 14 T outsert will be designed and made in-house with existing materials and proven technology (Florida-Bitter). The integration of such a resistive magnet, series-connected with a superconducting outsert to produce 45 T has not yet been shown. However, a 35 T SC hybrid magnet is now being constructed and a 45 T magnet could essentially use the same technology.

The first phase will consist of exploring the options for a specific technology, resulting in a preliminary design. We expect that design efforts will result within three years from the start of the project in a SCCF hybrid magnet Final Coil Design. The construction of the outsert and integration with the insert may take another two or three years. Thus the time span would be 5 to 6 years for the completion of the new system. If this could be realized it would be the first hybrid magnet ever to be completed in time.

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