KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

KNAW-Agenda Grootschalige Onderzoeksfaciliteiten

Format nadere uitwerking van een ingezonden voorstel

Dit format is bedoeld voor voorstellen die door de Commissie KNAW-Agenda Grootschalige Onderzoekfaciliteiten zijn geselecteerd voor nadere uitwerking. Hieronder wordt nog even het doel en de achtergrond van deze agenda toegelicht.

KNAW-agenda grootschalige onderzoeksfaciliteiten
Begin 2016 zal de KNAW haar agenda Grootschalige Onderzoeksfaciliteiten uitbrengen met daarin een selectie van grote onderzoeksfaciliteiten die in de iets verdere toekomst - rond of na 2025 - wenselijk zijn voor vernieuwend wetenschappelijk werk aan de grenzen van onze kennis én daarmee bijdragen aan de internationale positionering van sterke Nederlandse onderzoeksgroepen. Het gaat hierbij nadrukkelijk om ideeën voor faciliteiten die nog in het beginstadium zijn van ontwikkeling of ideevorming, niet om faciliteiten die al op korte termijn op de nationale of Europese *roadmap* zouden kunnen komen.

Waarom een KNAW-agenda?
Grootschalige onderzoeksfaciliteiten zijn belangrijk voor wetenschappelijke vooruitgang en versterking van vakgebieden. Gezien de benodigde investeringen is een langetermijnvisie noodzakelijk, met duidelijke keuzes en een zorgvuldige planning. De KNAW wil de gedachtenvorming rond dit onderwerp stimuleren door wetenschappers in Nederland te inspireren plannen te maken voor de bouw en exploitatie van grootschalige onderzoeksfaciliteiten. Hiermee hoopt de Akademie te bereiken dat Nederlandse wetenschappers wensen en ambities formuleren over de gedroomde grootschalige onderzoeksfaciliteiten van de toekomst.

Algemene aanwijzingen voor de uitwerking
U wordt gevraagd om de verkorte beschrijving van de faciliteit die u heeft ingediend bij onze oproep eerder dit jaar verder uit te werken. We vragen u hiertoe de vragen uit onderstaande format uit te werken en toe te lichten.
Het format is "vrij" in de zin dat u niet perse dit formulier met een tabelstructuur in te vullen. U mag uw eigen document maken, mits alle vragen zo volledig mogelijk en in deze volgorde aan bod komen.

Uw totale voorstel mag **maximaal 25 bladzijden** (lettergrootte 10 pt) bedragen.
De uitwerking mag in het Nederlands of Engels.

Uw uitgewerkte voorstel moet **uiterlijk 11 januari 2016** worden ingediend per email bij arie.korbijn@knaw.nl.

I. VOORSTEL ALGEMEEN

Acroniem	60T-DC
Naam van de infrastructuur	60 tesla continous magnetic field facility
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Functie	Director
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KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

	dr. F. Wijnen dr. M. van Breukelen – all HFML
Naam contactpersoon/ mede-indiener	dr. M. van Breukelen
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Samenvatting

Geeft korte samenvatting van deze faciliteit in termen van werking, wetenschappelijke voordelen etc. (max 350 woorden).

The 60 tesla continuous magnetic field facility (60T-DC) is a new international research facility that aims to construct and house the world's strongest steady-state or dc magnet. It would facilitate pioneering research in a number of diverse scientific domains, including soft and hard condensed matter physics, supramolecular chemistry, biomedicine and astrophysics. The system itself would require a revolution in technical design, materials development and international collaboration. It would build upon the global reputation of the High Field Magnet Laboratory (HFML) in Nijmegen and its excellent track record of innovative research on new materials like Nobel prize winning graphene and would attract many top-class researchers to the Netherlands. In short, it would make the Netherlands *the* global centre for high magnetic field research.

High magnetic fields define a frontier in scientific endeavour, an arena in which new discoveries are often made. Many of these discoveries, such as the fractional and integer quantum Hall effects, and the development of field-induced drug encapsulation, had not been predicted prior to their discovery, and without the development of high field installations, would have stayed undiscovered. This propensity for serendipity and discovery is what makes research at high magnetic field facilities like HFML unique and distinct from many of the other large-scale research infrastructures in which Dutch scientists ply their trade. Increased field strength also leads to enhanced resolution, particularly in resonant techniques such as nuclear magnetic resonance and ion cyclotron resonance. It also facilitates the development of new experimental techniques that reveal new phenomena or provide new insights into existing outstanding problems across a broad spectrum of the scientific disciplines. And each major breakthrough in magnet technology and experimental capability is often the catalyst for new scientific activity and discovery, which in turn feeds into the next cycle of technological innovation and breakthrough.

The 60T-DC facility envisaged here is exactly that - a catalyst for new scientific activity that requires its own revolution in conductor technology and magnet design. The prospect of a similar revolution in scientific discovery is what drives our collective vision.

Kernwoorden

Geef maximaal 8 kernwoorden die de faciliteit typeren.

Condensed matter physics, Nanotechnology, Physical chemistry, Medicine, Advanced Materials

II. VOORSTEL INHOUDELIJKE UITWERKING

A. SCIENCE AND TECHNICAL CASE

Volledig nieuwe faciliteit of verbetering van reeds bestaande

– Beschrijf in hoeverre het hier een geheel nieuw idee betreft of een verbetering of opvolging van een reeds bestaande faciliteit.

While HFML itself has been established now for almost 15 years, the 60T-DC facility is of an altogether different scale, requiring a separate building with its own dedicated power and cooling installations as well as unprecedented international cooperation. In that sense, this facility should be considered as an entirely new facility, one that is distinct from the HFML and its operation.

It also represents something entirely new on the international landscape. The largest continuous magnetic field in current operation is the 45 T hybrid magnet at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee in Florida. This magnet comprises an 11.5 T superconducting outsert magnet and a 33.5 T (Bitter-type) resistive magnet insert – hence the term 'hybrid'. The two magnets are operated in parallel from two separate power supplies. Similar systems are currently being constructed at HFML and at the Laboratoire de Champs Magnetiques Intenses in Grenoble (LNCMI-G) as well as at the Chinese High Magnetic Field Laboratory (CHMFL) in Hefei. As mentioned above, it is widely believed that a 60 T dc magnet would require an altogether new design concept and would represent a step-change in current-carrying conductor performance.

Science Case

– Geef een algemene introductie van de wetenschappelijke waarde van de faciliteit.

A magnetic field is a very important thermodynamic parameter (like temperature or pressure) that influences the state of *any* material system in a well-defined way. The versatility and universality of magnetic fields as a research tool lies in their coupling to the charge and spin of electrons that essentially constitute all matter. More specifically, the application of a magnetic field adds a new force (the Lorentz force) to charged particles, lifts spin degeneracy, changes the density of states of electronic systems, adds a new length scale (the magnetic length) and breaks time reversal symmetry. Apart from the quantum mechanical zero point motion, a magnetic field adds no extra energy to a system and its effect is therefore generally non-invasive and perfectly reversible. Research in magnetic fields has also led to numerous applications like nuclear magnetic resonance (NMR), electron spin resonance (ESR) and magnetic resonance imaging or MRI.

High magnetic fields have enabled major breakthroughs in science and have led to significant improvements in the nature of health care. Magnetism, and the use of magnetic fields, has been essential for many pioneering discoveries that have led, among other things, to 15 Nobel prizes in Physics, Chemistry and Medicine. Though many magnetic-field-based research techniques are standard and can now be done with conventional, commercially available superconducting magnets (MRI-scanners, NMR and ESR spectrometers), much of the groundwork for their realisation has been performed in a few specialised facilities which provide field strengths more than twice those that are commercially available.

To remain at the forefront of science, such facilities require a high level of unique expertise and substantial capital investment. In this respect, high magnetic field installations are similar to other large scale research infrastructures such as neutron, X-ray and synchrotron facilities, though their investment and exploitation budgets are, on average, one order of magnitude lower than any of the other large-scale facilities referred to above.

– Beschrijf de wetenschappelijke voordelen en verwachte doorbraken.

Research in high-magnetic fields has, to a large extent, been focused on the study of "hard" condensed matter systems, i.e. solids, surfaces or structures that are formed from periodic lattices. Materials may be either electrical conductors or insulators, whose conductivities may differ by many orders of magnitude, even at room temperature. At low temperatures, some materials are *superconductors*, which can carry currents with no resistance at all. In many systems, both insulators and conductors, electrons on individual atoms can develop *magnetic moments*, which may order at low temperatures in a variety of ways. Magnetic fields provide a way for studying the physical properties of these systems close to their phase transition, and in some cases, may even be strong enough to directly influence these transitions themselves. Indeed, there are a number of examples of a large magnetic field inducing a superconducting state in an insulator (i.e. effectively changing the electrical resistance from infinite to zero), or conversely, destroying superconductivity to reveal an insulating ground state, changing the effective dimensionality of electron flow in a metal, destroying long-range magnetic order or even establishing magnetic order in a hitherto non-magnetic system.

Much of the research effort has been devoted to understanding how such a huge diversity in the macroscopic behaviour arises, and how ultimately to exploit this behaviour to illicit new functionality in (nano)structures and devices. With increased understanding comes the ability to design and optimize materials to attain desired technological goals, and, on occasion, to conceive of altogether new technologies that impact profoundly on our daily lives.

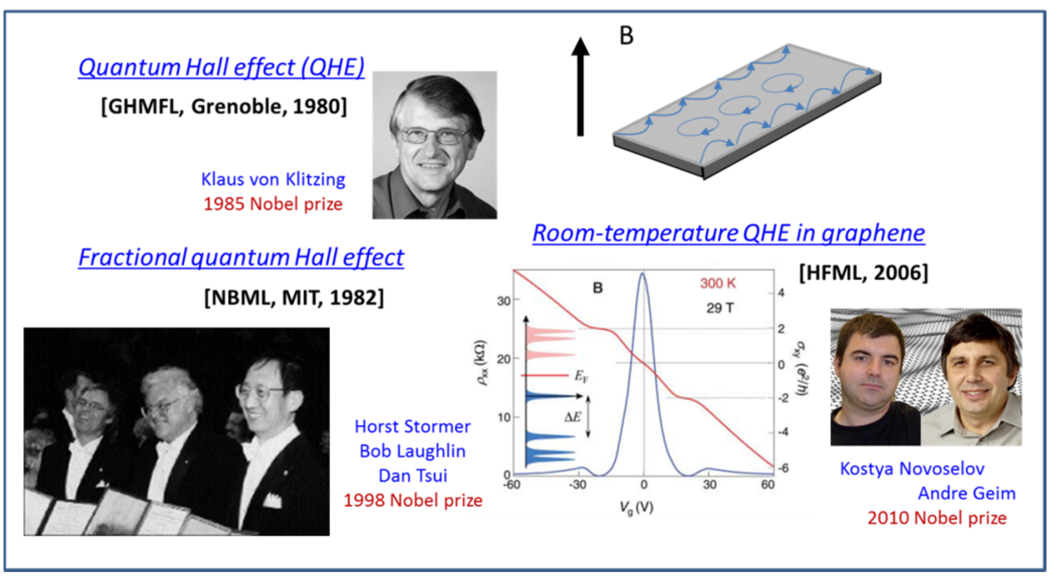

Figure 1: *Examples of seminal discoveries at dc (static) high magnetic field facilities over the years.*

The scientific motivation to pursue ever higher field environments and to invest in their generation is that the discovery of new physical phenomena and new phases of condensed matter are very often made at the highest available fields as under these conditions new phenomena are most readily accessible. While it is difficult, if not impossible, to anticipate what breakthroughs will be achieved by such a facility, it is certainly worthwhile taking an historical perspective of the role of dc magnetic field facilities in previous seminal discoveries. Notable cases of new physical phenomena that have been discovered at dc field facilities are the quantum Hall effect (GHMFL, Grenoble 1980 – Nobel Prize in Physics 1985), the fractional quantum Hall effect (Francis Bitter National Magnet Laboratory, MIT, Boston 1982 – Nobel Prize in Physics 1998), and the room temperature quantum Hall effect in graphene (HFML, Nijmegen 2005 – Nobel Prize in Physics 2010) – see Figure 1. Other examples include quantum critical states in rare-earth intermetallics, novel types of magnetism and magnetic-field-induced levitation of living organisms.

An additional motivation to use high magnetic fields in experiments and to invest in expanding their range of application is that new discoveries in technologically important materials, such as GMR devices, high electron mobility transistors, high temperature superconductors and graphene, are frequently made at the highest available magnetic fields. Moreover, high magnetic fields are very often involved in the first phase of the innovation cycle at the early stages of new material research, when sample quality has not yet been optimised. One example is in the use of quantum oscillations to map out the Fermi surface of conducting materials (the locus in reciprocal space of the most energetic electrons that are chiefly responsible for its gross macroscopic behaviour). The amplitude of quantum oscillations grows exponentially with increasing magnetic field and the more disordered the material, the faster the exponential growth. As shown in the left panel of Figure 2, for example, increasing the field scale from 45 T to 60 T can result in a 100-fold increase in the quantum oscillation amplitude for a typically impure correlated electron system.

Over the last few years, high magnetic field research has been extended to the investigation of soft condensed matter. This class of materials can be readily manipulated by external forces (mechanical, electric or magnetic) or thermal stress, because they are held together by relatively weak non-covalent interactions. All those materials are seemingly non-magnetic (diamagnetic), but the application of a high magnetic field can lead to macroscopic alignment of the material, making use of the torque exerted by the field on any system with an anisotropic diamagnetic susceptibility. Full alignment often results in improved electrical, magnetic, optical or magnetic properties of the bulk material. Alternatively, magnetic torques can be used to control the internal structure of soft matter down to the nanoscale, resulting in deformation or shape changes that can be used in microfluidics and drug delivery applications. Application of magnetic field gradients also allows magnetic forces to be generated that are able to purify mixtures (magnetic separation) or to counterbalance the force of gravity (magnetic levitation), providing a platform for microgravity research on Earth.

Experiments on soft condensed matter invariably require long times (e.g. to study plant growth, cell division etc. in reduced or zero gravity). As a result, almost all high field research in the soft matter realm is carried out at continuous, rather than at pulsed field facilities. The force exerted on an object in a field gradient grows as the square of the magnetic field strength. Thus, as shown in the left panel of Figure 2, by increasing the maximum field strength for a continuous magnet from 45 T to 60 T, this ‘levitation’ force can be effectively double those currently achievable with present technologies, allowing larger assemblies of molecules, cells and organisms to be levitated and a wider range of chemical and biological processes to be studied under zero or micro-gravity conditions.

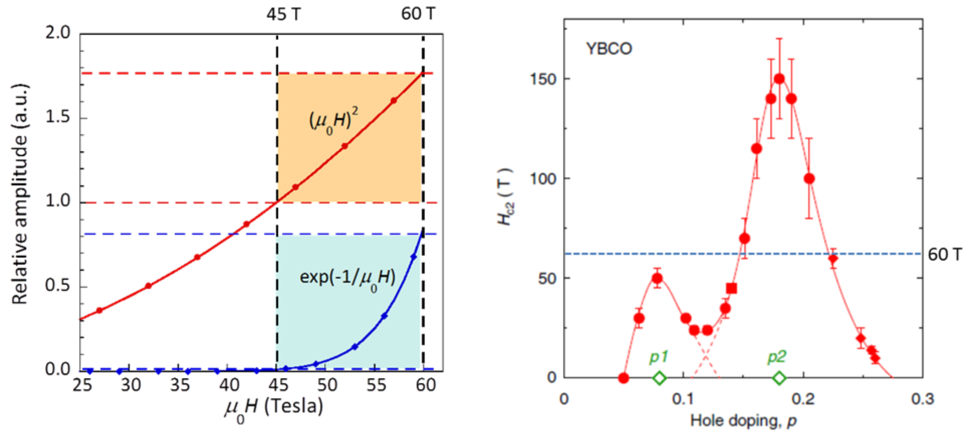

Figure 2: *Left panel: Schematic illustrating the expected gain in amplitude of various effects and signals that grow either quadratically (e.g. levitation forces) or exponentially (e.g. amplitude of quantum oscillations) in raising the ceiling for dc magnets from 45 T to 60 T. Right panel: Doping dependence of the upper critical field in a cuprate high temperature superconductor, indicating that a field of 60 T would allow access to the normal state across the entire underdoped region of the phase diagram below p = 0.15 [Grissonanche et al., Nature Commun.* ***5****, 3280 (2014)].*

A 60 T system would provide a world-unique environment, in which one could manipulate and probe new materials and novel phases with the whole gamut of spectroscopic, thermodynamic and transport measurements, without the time limitation (milliseconds) of pulse field experiments and thereby gain unprecedented insight into the emergence and nature of new phenomena. One would be able to access the electronic (zero-temperature) ground state of superconducting and magnetic systems with ever higher interaction strengths and study with atomic precision the self-organization of electrons and other fermionic or bosonic entities in (field-induced) physical states that were previously considered unattainable. The right panel of Figure 2 shows, for example, how a field of 60 T exposes the normal (metallic) state of cuprate high-temperature superconductors over the entire doping range below optimal doping (i.e. p = 0.15, the doping level corresponding to the maximal transition temperature), allowing one to probe directly the electronic ground state out of which high temperature superconductivity emerges.

Examples of key scientific targets of such a 60T-DC facility would be the development of magnetic storage media with ever shorter length and time scales, a resolution of the mysteries of chirality and its specific role in living organisms, an identification of the origin of high-temperature superconductivity and the search for new physics beyond the fractional quantum Hall effect.

In addition to the science case, research using high magnetic fields has proven to be a critical tool in solving problems of technological relevance. Indeed, many of the most-highly-demanded products in today's marketplace involve technology whose development was enabled, in part, by research using high magnetic fields. And magnetic fields continue to be used to attack many problems of scientific and technological interest. One of the current problems being addressed with high field research is in energy generation and storage. NMR has been used as an effective tool to probe the transport of Li ions during charge/discharge cycling of Li batteries where gaining a fundamental understanding of how Li dendrites grow is necessary to optimize battery design. As another example, Ion Cyclotron Resonance (ICR) has proven to be an essential analytical tool for understanding oil pipeline-clogging deposits and oil-spill pollution. Given the important role that high fields have played in past technological advances, one expects that many of the technological advances of tomorrow will be similarly based on research involving high magnetic fields.

At this point, it is worth raising a note of caution, or at the very least, a point of clarification. The magnetic field requirements, specifically the homogeneity requirements, of the different techniques described above are extremely varied. NMR, for example, demands the highest levels of homogeneity over the probing volume, to a few parts in a million. Microgravity experiments, on the other hand, require essentially the opposite, i.e. they are only viable in the presence of a strong field gradient. It is therefore impossible to fulfil all such requirements in a single magnet. In consideration of the ultimate design of the 60T-DC magnet, therefore, the various goals and requirements of the individual research fields will need to be clearly defined, so that the optimal conditions can be identified. A workshop to discuss all the scientific opportunities of a 60 T-DC magnet system is envisaged around the beginning of 2017. It is the intention of the KNAW proposal team to host the workshop here in the Netherlands, the goal of which will be to set out the scientific case for such a magnet system, and to inform and determine the final design requirements for the magnet itself.

– Beschrijf hoe deze faciliteit zich verhoudt tot alternatieve faciliteiten/onderzoeksmethoden.

As mentioned above, the world's strongest continuous field magnet in current operation is the 45 T hybrid magnet at the NHMFL in Tallahassee, Florida. Since its completion in the early 2000's, the 45 T hybrid has been heavily overbooked and many important discoveries have been made there. The HFML is currently constructing what will be Europe's first 45T-class hybrid magnet comprising a 12 T superconducting outsert and a 33 T resistive insert. The hybrid magnet, an NWO-Groot proposal, has taken 10 years to construct. Its magnetic field strength matches that of the hybrid magnet in Tallahassee, though significantly, two others are currently under construction in Hefei, China and in Grenoble, France. Hence, within the next 3-4 years, a 45 T continuous field platform will be created on three continents, raising the prospect of significant new discoveries in a broad range of scientific disciplines. In the realm of NMR, the NHMFL has embarked on an ambitious program to develop a high-homogeneity 36 T series-connected hybrid (i.e. the superconducting and resistive components are powered from the same supply) for 1.2 GHz NMR spectroscopy that will revolutionise the NMR field for a number of years to come. The question then is, though, what next? What is the goal for magnetic field science and technology in the coming 20 years?

Over the years, *pulsed* magnetic field facilities, requiring large stored energies, e.g. through a capacitor bank or flywheel, have offered roughly twice the maximum field intensity of continuous or dc field facilities such as the HFML, but as the field rises and decays within a few tens of milliseconds, the range of pulsed-field applications has been limited. *Continuous* fields, on the other hand, can be employed with almost all thinkable experiments and are only limited in their field strength. The dream of those within the community, therefore, is to make accessible field strengths historically the preserve of pulsed field facilities to the continuous domain. Until only recently, 60 T was widely regarded as the maximal field scale available through standard pulsed field technology, and indeed, the current state of the art for so-called long pulses (i.e. those lasting up to 100 ms) is presently the 60 T system at the Los Alamos high field facility in the USA. With a 60 T continuous field, lasting several hours in duration, the possibilities for new frontiers are, quite simply, endless.

With their larger field ranges, pulsed magnetic fields would still be the medium of choice for exploring phase space and for searching for new magnetic, electronic or multiferroic phases.

The 60 T magnet would, on the other hand, enable a raft of different experiments to be performed that simply could not be done with a pulsed field system. Techniques requiring dc magnetic fields include ultra-sensitive voltage measurements that allow high precision parametric studies of the electrical resistance, heat capacity, susceptibility and thermopower, as well as optical spectroscopies, performed over a wide range of frequencies. The ability to carry out these measurements in ultra-high fields, already proven in zero field to provide crucial information, has the potential to open up whole new fields of research and technology.

In addition to facilitating important thermodynamic and (thermal) transport measurements on condensed matter systems up to 60 T, such a magnet could also be used to enable persistent experiments, i.e. those that require continuous magnet operation more than one day in duration, to be performed up to field scales of, say, 50 T (depending on the cooling capacity of the system). Fourier-transform scanning tunnelling microscopy is an increasingly important tool in the study of unconventional superconductors and novel metallic ground states with atomic resolution, but which currently has a field threshold set by conventional superconducting magnets of order 20 T. While high temperature superconducting magnets currently under development may raise that barrier up to 32 T, the 60 T system would allow access to spectroscopic information at unprecedented field scales and to study processes, such as the fractional quantum Hall effect at the atomic scale. It would also enable long-duration chemical or biological experiments, such as crystal growth and cell division experiments to be performed under tuneable gravity conditions.

Finally, in biological and chemical systems, high-field NMR performed on complex molecules has become indispensable for analyzing molecular structure and motion. Since resolution and sensitivity of NMR measurements increases with magnetic field, high magnetic field research translates into leadership in the investigation of the structural and functional properties of biological systems, as well as the properties of technologically important materials. New frontiers in biological and medical imaging of human physiology and metabolism would be enabled by access to higher fields than available currently. The impact of high-field studies of biological and chemical systems is amplified by an expanding variety of techniques, including multidimensional NMR, Dynamic Nuclear Polarization, Functional Magnetic Resonance Imaging, in vivo Magnetic Resonance Spectroscopy and Fourier Transform Ion Cyclotron Resonance. Applications of these and other techniques depend on increasing magnetic field strengths, with associated facilities.

Technical case

- Geef op hoofdlijnen een technische beschrijving van de faciliteit. Hoe zit de faciliteit in elkaar en hoe werkt het?

In general a high field magnet consists of a set of nested cylindrical coils with a solenoidal winding lay-out to efficiently accommodate high current density conductors as close as possible to the accessible high field region. The actual construction of a magnet is always a compromise bounded by constraints of mechanical stress, available electrical power, allowable coil temperature, conductive properties of the conductor material and the availability of required conductor material in a proper shape and with predictive properties. Though differently expressed this holds for both resistive and superconducting magnets.

Because of these constraints, very high field magnets rapidly grow in volume and in stored energy necessitating a modest to low self-inductance which in turn implies high currents in the range of 20-100 kA and a large conductor cross section of 5-50 cm^2. This is especially relevant in case a coil fails and a very fast decay of the current is demanded; a high current and a small self-inductance enable a relatively fast current decay at a given maximum allowable potential difference across the coil terminals (usually about 10 kV). Superconductors however are produced as wires or tapes with a typical cross section of 1-2 mm^2, which limits their current carrying capacity at high fields to only a few hundred amperes. Multi-kA conductors are therefore cabled structures containing 100-1000 superconducting wires or tapes. As mentioned, for mechanical strength and thermal stability such a cable is packed inside a reinforcing jacket of steel or copper.

At present it should be expected that a quasi-DC 60 T magnet shall be a combination of resistive and superconducting magnet technologies. The principal reasons for this presumption are scale and cost.

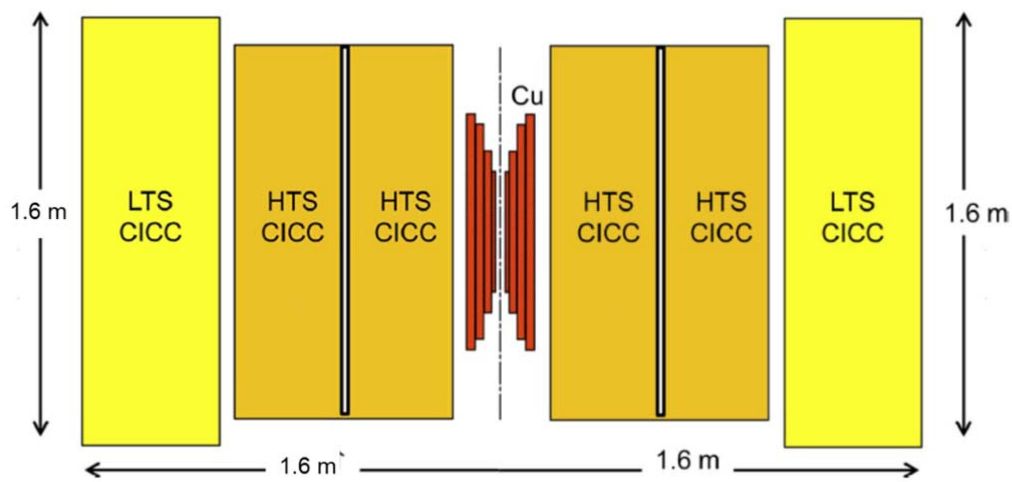

Figure 3. *Preliminary concept design for a 60 T 'tri-brid' magnet. The copper Bitter magnet coils at the centre are surrounded by high-temperature superconducting cable-in-conduit conductors (HTS-CICC) that are in turn surrounded by a low-T_c superconducting outsert [M. Bird, IEEE transactions on Applied Superconductivity **25**, (2015)].*

Figure 3 shows a preliminary design concept for a 'tri-brid' 60 T magnet from the NHMFL, consisting of both low-T_c and high-T_c superconducting coils, in addition to an inner Bitter resistive magnet. All specialized high field magnet laboratories have built up extensive experience with design optimization and construction of 20-30 MW water-cooled resistive magnets employing pure copper and copper alloy conductors. For the existing and presently developed hybrid magnets the only option to reach higher fields within the available power constraints for the resistive magnets is to utilize traditional low temperature superconductors like $NbSn_3$ and NbTi for the large outsert magnet that surrounds the resistive magnet. However, their superconducting and mechanical properties limit their field contribution to about 14 tesla, which would be insufficient to achieve a 60 T magnet without a major extension of the power and cooling capacity for the resistive coils. Apart from that it is still unclear yet if even with the available conductor materials and coil technologies such a hybrid system could reach 60 T at all.

With the advent, development and steady but slow performance improvements and industrial production upscaling of high-Tc superconductors (HTc) like BiSrCaCuO and RECaCuO (RE=rare earth) acceptable current densities at magnetic fields well above 30 T can be achieved, offering a viable but presently expensive option towards the generation of much higher fields than is presently feasible. Important and promising steps are being made towards single wire, 30^+ T class all superconducting magnets exceeding impressively the long lasting 22 T limit for Nb_3Sn/NbTi superconducting magnets. It should be noted however that despite their high critical temperature of around 100 K HTc conductors offer sufficient performance at very high fields only when operated at the lowest reasonably achievable coil temperature, e.g. 5 K for supercritical helium cooled systems.

For all magnets, regardless of which technology is used, the amount of energy stored in the magnet depends on natural constants (the permeability of free space), the square of the magnetic field, and the volume where this field is present. Therefore in all high-field magnets with a reasonable measuring volume the amount of energy stored is enormous. For larger magnets such as hybrids, 100-200 MJ stored energy is not uncommon. This enormous amount of stored energy requires that important safety precautions be implemented in the magnet's operation, since release of that stored energy over a short time period is comparable to the energy released by a small bomb. This energy is of particular concern for superconducting magnets since their relatively large self-inductance means they are unable to rapidly carry away that stored energy.

Though no concrete 60 T magnet design has been established yet, it is likely that such a system will contain both resistive and superconducting coils, powered either in parallel or in series. The inevitable reinforcement jacket for the superconductors increases their stiffness which in turn impedes winding a coil with a small radius. Therefore a magnet system that involves all three technologies will have a natural radial build: from inside out a resistive section, than a high-T_c superconducting section and finally a low-T_c superconducting section. On infrastructural level it has to be decided to what extent the power, cooling and cryogenic installations available at the existing high field magnet facility should or can be incorporated in the design and operation of such a facility. Therefore we can only state here that a 60 T facility at least comprises the following components:

Magnet system and experimental facility
- one or more nested resistive and superconducting magnets inside their own housing, with connections for water or cryogenic cooling lines, high current connections, diagnostic wire ports and superconducting bus bars and current leads
- a vibration free platform around the magnet system that gives the experimentalists access to the magnet's central bore and that facilitates placement of auxiliary equipment like pumps, cryogenic components, optical elements, vibration cancellation systems etc.
- a shielded guiding system for sensor and control wiring from the experiment to a distant instrument room

Power, control and cooling
- one or more new high current power converters to supply currents in the range of 40-100 kA to one or more magnet (sub-)systems
- high current/high voltage switching equipment to enable a quick disconnect of a magnet from its power converter
- dump resistors to absorb hundreds of MJ of energy in case of an emergency stop
- a cryogenic plant to supply cooling capacity of about 1 kW at 4.5 K and of 5-10 kW at 77K
- a cooling plant for the water-cooled resistive magnets
- a magnet control and monitoring system

Building
- a magnet hall with a typical size of 10x10x8 meters with adequate lifting equipment
- a control room for system operation and system control equipment
- an instrumentation room for experimentalists to install and employ measuring equipment
- a technical corridor between magnet hall and power & cooling facilities to accommodate high voltage c.q. high current bus bars, water cooling piping and cryo lines
- a fully equipped technical assembly and test hall for sub-magnet assembly and component test operations
- rooms for power converters, dump resistors and switching equipment
- rooms for the cryogenic plant and low quality space for high and low pressure helium gas storage and supply
- a room for the building safety and climate system
- offices for operators and technical support

– Beschrijf welke onderdelen/technieken beproefd zijn en welke geheel of gedeeltelijk nieuw?

The construction of magnets that operate at high fields is, and has always been, an engineering challenge. In the quest to generate ever higher magnetic field strengths, two issues have to be confronted. Firstly, the field of an energized electromagnet exerts forces on its own structure that increase as the square of the field strength, which will destroy it if not contained.

Secondly, if the electrical conductor of which the magnet is made is a normal metal, resistive heating produced by the electric currents can cause the magnet to fail. Superconducting magnets, in which the current is transported without resistance at sufficiently low temperatures minimize the risks associated with the latter. However superconductors have their own limitations. In particular, all superconducting materials have a critical magnetic field above which they can no longer support resistance-less current flow, and cannot be used in magnet construction. A major goal of research in high magnetic fields is to learn how to create superconductors with higher critical fields and to learn how to make magnets out of these materials.

Producing such magnetic fields requires not only world-class engineering but also the development of rare materials that must combine strength with good electrical conductance. The demands on magnets due to the Lorentz force are huge, and controlling them in all parts of the magnets—the winding body, the housing, and other components such as current leads—is a major design challenge. Design requirements are further complicated by the need to have the largest possible currents, and hence the largest forces, in a small volume near the magnet's central bore. Another restriction is the need to use some of the space in the magnet body for the flow of coolants to uniformly counter the heat generated by the currents flowing through the magnet. In the design of superconducting magnets, one must not only take into account the constraints imposed by the Lorentz force, which are the same as in resistive magnets, but also the poor mechanical properties of the superconducting material. This requires including in the design re-enforcing measures that sufficiently strengthens the magnet against the substantial Lorentz forces which similarly eats conductor space.

Uitdagingen en risico's

– Beschrijf de belangrijkste technische knelpunten en geef aan hoe deze opgelost zouden kunnen worden.

Most technology for power, control, cooling and building is available or may require a rather common but nevertheless huge engineering effort to meet the particular demands for the magnet system and its safe operation. The long lasting experience with the design, manufacturing and operation of resistive and hybrid magnets has created a sound foundation to define and manage these efforts with a strong involvement of experienced industrial partners. This is definitely not the case for the conductors needed for such large and high-field magnet systems.

Since the erection of a large magnet system is a rather rare event, the manufacturing of conductor and conductor materials usually takes place in small quantities on specific request of the developing party according to very specific requirements. Even for resistive magnets this is still a rather delicate issue illustrated by the fact that only one or two manufacturers world-wide are able or willing to deliver or develop relatively small quantities of less common Cu-alloy sheet or bulk materials. Exceptions for superconductors are large scale projects like LHC and ITER where the large volumes requested are also commercially attractive for candidate vendors and manufacturers. Any deviation however from an existing conductor design requires a long and costly iterative design-manufacturing-qualification process.

A single iteration step comprises conductor design, trial production steps (preferably with industrial involvement), prototype manufacturing and experimental performance verification on sub-assemblies and full-size conductors. Depending on the performance results and the technical feasibility of upscaling manufacturing processes it is even likely that design parameters or requirements on system level (like stability margins, system integrity during off-normal events or safety) have to be adapted necessitating another round of iterations.

B. INBEDDING

Hoe past dit voorstel in het (internationale) landschap van grote onderzoeksfaciliteiten?

– Hoe wordt de nationale toegang gegarandeerd?

Access to the HFML facility is currently organised centrally through the EMFL. All proposals for experiments, both in-house and external, member and non-member, Dutch, EU and non-EU, have to be submitted through a web-based application and are ranked by the EMFL Selection Committee (SelCom). Calls for proposals are held twice per year (deadlines May and November) with the outcomes announced one month later. Users are expected to use the facilities for scientific exploration with the aim of publishing their results in the scientific literature and successful applicants from publicly-funded research institutions obtain access free of charge. Applications for magnet time from private companies are currently considered on a case-by-case basis with the proviso that the work entailed (a) be novel and (b) could lead to a scientific publication in due course.

Proposals for the 60T-DC facility would have a different emphasis. While the key selection criteria like scientific quality, innovative character, quality of the proponent and past performance of the proposer(s) will be considered, evidence must also be provided of previous or preliminary work that had been carried out at other dc magnetic field facilities (i.e. up to 45 T).

It is important that scientific excellence be maintained as the fundamental selection criterion. We would therefore not be able to give any special dispensation to Dutch researchers.

– Sluit het aan op reeds bestaande faciliteiten?

The HFML in Nijmegen produces some of the world's highest continuous magnetic fields. These magnetic fields facilitate pioneering research in a number of diverse scientific domains, including soft and hard condensed matter physics and supramolecular chemistry, attracting many top-class researchers to the Netherlands. The HFML is scientifically successful, has a global reputation for both its in-house research and that of its user program, is committed to advanced materials research in line with the government's top sectors initiative and stimulates technology and innovation.

Radboud University (RU) and FOM jointly run HFML, with the shared goal of making it a global player. It plays a prominent role in the European Magnetic Field Laboratory (EMFL), a distributed network of established high field facilities (both continuous and pulsed) in the Netherlands, France and Germany. EMFL has been upgraded recently from the ESFRI roadmap to the landmark status after successfully establishing the legal entity EMFL-AISBL.

Just as HFML initiated the establishment of the European Magnetic Field Laboratory (EMFL, FP7 P3-project), so it has taken the lead in setting up the global high magnetic field forum. It thus currently enjoys an outstanding reputation within the international high field community, and so it aims to lead on any subsequent technical design study for a 60 T magnet system and be a driving force towards the realization of a truly world-leading instrument. HFML has the additional advantage that a free electron laser (FELIX Laboratory) can be coupled to it, a unique combination that is of enormous benefit to both the high field and free electron laser user communities.

– Zijn er voor zover bekend vergelijkbare ideeën (of al bestaande faciliteiten) in het buitenland? Zo ja, zou Nederland een aparte nationale faciliteit moeten hebben of betreft dit een internationale faciliteit op Europees of mondiaal niveau?

The construction of a 60 T hybrid system is a significant technical challenge. As described above, the final design of such a magnet will involve technology that has never been contemplated before, comprising resistive, low-T_c *and* high-T_c superconducting technology, for which a lot of expertise is already present in the Netherlands. It is obvious, already now, that it will take many years of development into high-temperature superconducting magnets and the intersection of the three different technologies before a complete design is contemplated. The scale of this task is such that it can only be achieved through global cooperation. A global forum of the world's high magnetic field facilities (HiFF) was held for the first time last year, at which the roadmap towards a 60 T continuous magnet was first discussed.

The USA National Research Council[1] recently made a compelling case for a 60 tesla hybrid magnet as a research tool in a wide variety of research areas. A roadmap towards a 60 T system is thus being formulated by the NHFML in Tallahassee, though it is recognised by all concerned in the US that realisation of the 60T-DC facility will inevitably involve major international collaboration and financial support.

[1] National Research Council: "Magnetic Field Science in the United States: Current Status and Future Directions", 2013

Hoe past het voorstel bij de NL sterktes van onderzoek?
The clearest argument one could make regarding why such a facility should be housed here in the Netherlands is perhaps one of history. The Dutch have a tremendous legacy in the field of magnetism and magnetic field science and indeed, two of the most important effects induced by a magnetic field, the Zeeman effect and the Lorentz force, are named after Dutch scientists. The important notion that an electron possesses an intrinsic spin was also first conceived by two Dutch nationals, Goudsmit and Uhlenbeck. The Lorentz force is also responsible for an unusual effect that occurs in metals, whereby its magnetization oscillates as a function of the applied field, now known as the de Haas-van Alphen effect after its discoverers. It is an effect that is now used ubiquitously in high magnetic field facilities around the world to determine many important physical properties of metals and superconductors. Last, but not least, superconductivity, the key phenomenon by which the 60T-DC magnet will be realized, was of course a Dutch discovery, in the laboratory of Kamerlingh Onnes in Leiden in 1903. In more modern times, the role of HFML, firstly in the discovery of the room-temperature quantum Hall effect in graphene, and secondly in its association with the 2010 Nobel Laureates Andre Geim and Kostya Novoselov, is widely recognised and appreciated.
Beschrijf de voordelen/belang voor NL indien zo'n faciliteit zou worden gerealiseerd. Dit mogen zowel wetenschappelijke als economische of maatschappelijke voordelen zijn.
In addition to the long and successful legacy of Dutch science and scientists in the realm of magnetic field research, there is also a strong economic case for why its construction here in the Netherlands would be of benefit. In the course of commissioning the existing magnet installation, the HFML interacted with a number of leading Dutch technology companies. In many cases, this interaction has led to a number of additional benefits for many of the companies concerned as well as to an overall strengthening of Dutch industrial competitiveness. In addition, all PhD students that graduated from HFML have successfully found jobs either in research institutes or industry. Foreign PhD students especially often find jobs in Dutch industry and remain in the Netherlands. In this way, the HFML contributes in no small way to the brain-gain. A facility of the scale and importance of the 60T-DC facility would only amplify these collective benefits to the Dutch society. A final benefit of hosting the 60T-DC facility on Dutch soil, and in particular in Nijmegen, is the potential to couple the 60 T magnet system to the FELIX free-electron-laser facility also based at Radboud University. The Netherlands is currently the only country worldwide with such a combination of intense, tunable THz radiation and intense magnetic fields. THz free-electron-lasers are an especially powerful probe of high-field phenomena, since typical frequencies of many resonance phenomena, such as electron spin resonance and cyclotron resonance, fall in the 1-10 THz range for fields between 40 and 60 T (see Figure 4). Moreover, their energy scale is well matched to excitation spectra in quantum solids, allowing many interesting physical phenomena (see Figure 4 for some important examples) to be studied using, for example, time-resolved spectroscopy. The presence of the FELIX laboratory and its already successful coupling to the HFML may, in the end, be a strong argument in favour of securing the 60T-DC facility for the Netherlands.

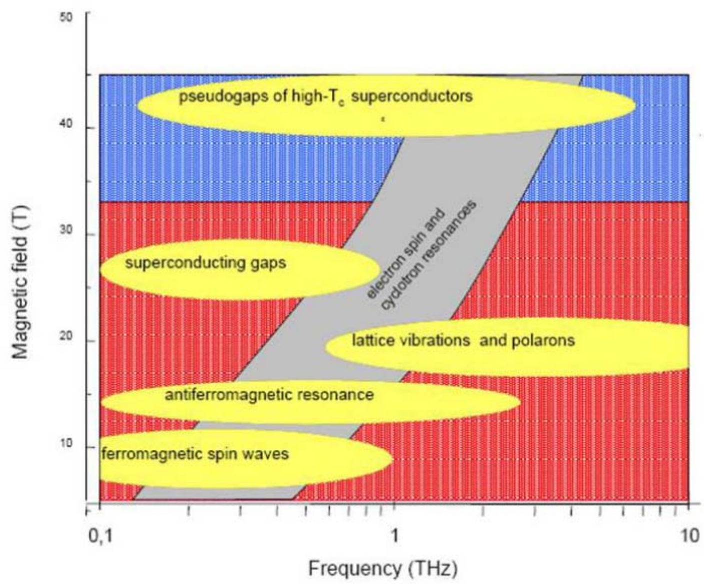

Figure 4. *Typical energies in THZ, of various physical phenomena in magnetic and superconducting systems in fields up to 45T, showing that the combination of intense far infrared generated with free electron lasers combined with high magnetic fields has great promises for innovative research [National Research Council: "Magnetic Field Science in the United States: Current Status and Future Directions", (2013)] .*

C. ORGANISATIE en FINANCIËN

Organisatie

Beschrijf de (mogelijke) organisatiestructuur. Geef ook aan of er al een begin van organisatievorming is.

It is clear that the development of a 60 T hybrid or tri-brid magnet system will constitute an enormous financial and technological challenge. It will therefore be necessary to combine all global experience and financial clout in this field to bring this challenge to a success. Developing a strategy that ensures that the conditions to meet this challenge are met by encouraging international collaboration as much as possible will help to ensure that the conditions needed to meet these challenges are in place.

Fortunately, there exists already a very intense informal collaboration among the main high magnetic field facilities worldwide and knowledge is shared very effectively. All magnet laboratories have close connections to various industries that develop systems for installation at the laboratories or provide specific materials needed to produce high field magnets. The extreme conditions required to produce and use the highest fields (high energy or power densities, extreme mechanical loads, high current densities, high stability of the power source, etc.) often go beyond standard industrial products and thus push the limits of the industries involved. Information about possible suppliers is shared among the laboratories, which often leads to orders for these industries. Parts like housings and cables for the CICC require specialized windings and jacketing facilities that often are fabricated on different continents and shipped back and forth between the laboratories.

Thus, while a formal organisational structure is not yet in place, the important foundations of international collaboration and the cross-fertilization of ideas are very much in evidence. The envisaged, concerted R&D effort will ultimately require a strong, flexible and efficient project management and well-structured administrative, communication and documentation systems. For this, the global high magnetic field forum (HiFF) will have a key role to play, not only by coordinating the development of the organizational structure, but also by encouraging its members to consult with their home organizations and with large-scale institutions like CERN and ITER in order to learn from their experiences.

Financiering

Geef een globale beschrijving van de business case. Hoe zou deze faciliteit gefinancierd kunnen worden? Ga hierbij in de drie fases: ontwikkeling, bouw en exploitatie.

As mentioned above, the first important step is the organization of a workshop to discuss the scientific opportunities of a 60 T-DC magnet system with the global research community. This workshop will be financed by the different high magnetic field laboratories, with additional support from interested parties and sponsors, and it is our intention to host the workshop here in the Netherlands at the end of 2016 or at the beginning of 2017. This workshop will then help to set out the scientific case for such a magnet system, and to inform and determine the final design requirements for the magnet itself. One major issue to resolve is the level of homogeneity of such a magnet. In the NMR and FT-ICR research arena (among others), optimized homogeneity is as fundamental a parameter as ultimate field strength and it will be important to take into account the requirements (both scientific and technical) of these communities for a 60 T-class system before the final design parameters are established.

Following the outcome of the science workshop, an application will then be made to Horizon 2020 to complete a design study for the 60 T-DC magnet. This 4-year grant proposal will request support of around 3 M€ to explore the limits of the different technologies and their combination, and to look at the development of materials capable of withstanding the extraordinary forces that will be generated by the vast currents circulating in the various coils. A similar design study will be carried out by the NHFML in the United States, though it has already been formally agreed (through the Global High Magnetic Field Forum) that information, technology and best practice will be shared as far as it is commercially viable. The global high-field community has a very good record of scientific and technological collaboration, while retaining the competition between laboratories important for advancing magnet technology and producing scientific results.

At the end of this design stage, a concept design will be produced and a reliable estimate of the total costs involved will be obtained. It is still an open question how the final magnet construction will be funded, but given the expected costs, it is envisaged that this will be a global endeavour and that funds will be sought from a consortium of interested countries. The final location of such a magnet, however, is still to be decided of course. However, in taking the lead on such a venture, the Netherlands could be recognised early on as a viable location.

Regarding the business case itself, magnetic fields are central to the operation of many devices crucial for the functioning of a modern society. For example, electric motors and generators of electrical power, read-out heads in magnetic disk memories, as well as MRI scanners. For motors and generators, and many other electromechanical devices, increases in strength of the magnetic fields employed could lead to important improvements in performance, for example by achieving larger power output in a smaller volume. MRI devices require the highest available fields to achieve satisfactory resolution and sensitivity, and the magnets used in these devices are constantly pushing the limits of magnetic field technology. Very high fields are necessary for many crucial research applications in materials science, chemistry, and biology. The success of these experiments may have major impacts on health care and technology. High magnetic fields in very large volumes are also required for accelerators in high-energy physics, and in plasma research aimed at the realization of controlled nuclear fusion.

Thus any advancement in the realm of high magnetic field science and technology has the potential to have an impact across a wide spectrum of modern society. High magnetic fields form part of the fabric of industrial innovation, contributing in three distinct ways: (i) they are often involved in the very early stages of research into new technological materials, relevant to the topsectors initiative, (ii) they can be used to change or improve a material's properties, and (iii) the technological challenges raised in attaining an operational high field installation invariably stimulate technical development programs in a number of related sectors. For example, HFML is involved in the realisation of a 45 T hybrid magnet which consists of a large 12 T superconducting magnet and a 33 T resistive insert. In particular, the realisation of the 12 T field is a major technological challenge. The immense forces, the high current densities, the operation at 4.5 K, and the strong magnetic fields experienced by the superconductor require the most sophisticated superconducting technology. Only a very few companies and research institutes in the world are working in this field and they are eager to collaborate with the HFML. This technology is important, for instance, for the fusion reactor ITER, and the hybrid project is linked to that community. In the Netherlands, we therefore contribute to the development and know-how of applied superconducting technology. Finally, in constructing the normal resistive magnets, we also collaborate with several smaller companies for specialised mechanical work (etching, laser cutting, punching etc.). With this type of mechanical work, extreme precision and reliability is required, since at maximum field the magnets experience conditions very near their mechanical and thermal limits and even minor defects can immediately lead to the destruction of a coil.