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Developments at the High Field Magnet Laboratory in Nijmegen

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Abstract The High Field Magnet Laboratory at the Radboud University Nijmegen is rapidly expanding its capabilities. The developments encompass both organizational changes and new possibilities for research. The organization of the HFML was strengthened as a consequence of stronger participation of the Foundation for Fundamental Research on Matter (FOM), and an increase of the core-funding. This change makes that HFML is now considered on a national level as large research facility that operates at an international scale. At the same time work is underway to build new and powerful magnets, and provide electromagnetic radiation for magneto-spectroscopic studies.

Electromagnetic radiation in the infrared and far-infrared spectrum will soon be available in the HFML with wavelengths between 3 μm and 1.5 mm, produced by the 'FELIX' facility, comprising the long-wavelength free electron laser 'FLARE' that in September 2011 produced its first light and the free electron lasers that have been moved from Rijnhuizen to Nijmegen. In magnet technology great strides are made to make magnets available for the user community with unprecedented performance: late in 2012 we hope to commission a new all-resistive magnet system that will generate a steady magnetic field as high as 38 T, by fully exploiting the maximum power of the installation, i.e. 20 MW, and using all available improvements in the design and construction of 'Florida-Bitter' resistive magnets. We are also well underway with the design of a 45 T hybrid magnet system, using Nb_3Sn superconductors and wind-and-react Cable-in-Conduit technology.

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1 Introduction

Operation of the High Field Magnet Laboratory (HFML) at the Radboud University Nijmegen (RU) started in 2003 [1] with three 18 MW, 33 T resistive magnets, built in collaboration with the National High Magnetic Field Laboratory (NHMFL) in Tallahassee FL. We have since used the 'Florida-Bitter' design to develop and build a 50 mm bore 32 T magnet [2], and are now about to commission a 38 T resistive magnet with 32 mm clear bore [3], at the limit of what is possible with the power constraint of 20 MW. In the drive to provide our users even higher magnetic field strengths, we are working on a programme to develop a 45 T hybrid magnet system [4].

It is not only the quality of the magnetic fields that counts, but also the quality and availability of the equipment for a wide variety of experiments [5]. In recent years much work has been done on the implementation of measurement probes for magnetization and de Haas-van Alphen studies, but also on improvement of spectroscopy. In the near future the HFML will have access to infrared and far-infrared radiation produced by the free electron lasers FLARE and FELIX.

Users also need sufficient access to the magnets, and the Radboud University Nijmegen, the Foundation for Fundamental Research on Matter (FOM) and the Netherlands Organisation for Scientific Research (NWO) have all teamed up to increase the budget of HFML to a level where the installation can be exploited to its capacity. The way to full use has been prepared by extending the effective number of working hours and running the cooling installation almost 24 hours per day. At the same time several improvements of the cooling system were implemented, and the real time cooling capacity was increased by the addition of a third chiller to more than 5 MW, adequate to evacuate the average heat load during operation of the magnets. These improvements make that for most experiments the cooling capacity is almost never the limiting factor.

In this paper we will briefly highlight the design of the new 38 T resistive and 45 T hybrid magnets, and report the new possibilities for (far)infrared magneto-spectroscopy.

2 Organization and Scientific Program

In the years 2011 and 2012 HFML has increased its activities substantially through the increased funding that has been granted by NWO, FOM and RU. This increase is the result of the successful research in the past years and the fact that it was recognized that the low operational budget of the HFML, sufficient for about 1,000 magnet hours of use, allowed to exploit only a third of the technical capacity of the infrastructure. The organizational and financial injection also greatly strengthens the collaboration with the other high magnetic field laboratories in Europe, namely the pulsed magnetic field facility in Dresden (Hochfeld-Magnetlabor Dresden, HLD, at the

Fig. 1 The European Magnetic Field Laboratory (EMFL) is a collaboration of the High Field Magnet Laboratory in Nijmegen, the Laboratoire National des Champs Magnétiques Intenses in Grenoble and Toulouse, and the Hochfeld-Magnetlabor in Dresden (Color figure online)

Helmholtz Zentrum Dresden Rossendorf) and the Laboratoire National des Champs Magnétiques Intenses in Grenoble (LNCMI-G, DC-fields) and Toulouse (LNCMI-T, pulsed fields), both operated by the CNRS. All these laboratories are working together to form a joint European Magnetic Field Laboratory (EMFL, Fig. 1), based on a formal collaboration between the four autonomous laboratories. Through the EMFL common activities (like networking and coordinated user access, as organized now within the FP7 project EuroMagNET) will be continued while it also provides a permanent forum (independent of incidental EU funding) to share knowledge and expertise, coordinate structural collaboration (magnet technology and scientific experimentation) and external representation. The EMFL will become the representative of the most important activities of science in high magnetic fields in Europe and serve as a recognizable body that may accommodate future partners, represent the activity on a political level (EU and local) and strengthen the position of our area of science.

The main tasks of the HFML are

(i) to generate the highest possible DC magnetic fields,
(ii) to provide service to external users,
(iii) to perform its own research in high magnetic fields.

The magnet technology program covered in Sects. 3 and 4 concerns the first task. The second task can be measured in the number of magnet hours that is delivered and the number of guest researchers that have profited from the facility. Previously funding allowed 1,000 hours per year and with the budget increase this will grow to more than 2,000 per year. In 2011 we have already realized almost 50 % of this increase (1,450 hours), executing 49 different projects involving more than 70 external guest researchers. At the same time the demand of magnet time shows a steady increase, growing from 1680 for the two calls for proposals in 2010 to 2840 hours total for the last two calls. We expect that in the coming years we will reach our target and will come to full exploitation of the technical possibilities.

Parallel to that the in-house scientific program has become more clearly defined. The HFML works on the following research areas:

- low dimensional systems and semiconductors (topological insulators, graphene, quantum Hall effect, quantum dots),
- strongly correlated electron systems (high-T_c materials, pnictides, transition-metal-oxides),
- soft matter in high magnetic fields (self assembly, alignment, crystal growth in simulated microgravity, chirality).

These research lines cover the most promising areas of research in high magnetic fields and assure the presence of local staff with the right competences to be attractive for external users. The choice of topics ensures that experimental expertise in the area of low temperatures, thermodynamic measurements, optics and far-infrared is present in the HFML.

Thanks to the local research, sophisticated experimental set-ups like confocal microscopy (with sub-lambda resolution) with time-resolved spectra, thermoelectric measurement down to 50 mK, and Fourier spectroscopy in the far-infrared can now routinely be used. New experiments under development are femtosecond spectroscopy in high magnetic fields and Scanning Tunneling Microscopy (STM) at 33 T. This evolution fits in the laboratory's philosophy that it is necessary not only to offer the highest magnetic fields but also experimental possibilities in those fields matching state-of-the-art possibilities of experiments done with standard commercially available superconducting magnets.

3 The 38 T 'Florida-Bitter' Resistive Magnet

For the existing 33 T series of magnets the outer diameter is 610 mm, and to provide users with stronger magnets we have relaxed the constraint to 1 m, so that for the existing maximum power of 20 MW a 38 T resistive magnet could be designed. Beyond this size the tooling to fabricate the Bitter plates is becoming prohibitively expensive, and the coils impractically heavy. Whereas the innermost A_1-coil generates 1.19 T/kg, this number is reduced more than a factor 1000 to 1.12 mT/kg for the outermost E-coil in the present design. The coil was optimized for a maximum field of 37.5 T at an operating current of 39.5 kA, and may need a bit more than 500 V to produce its highest field. The coil consists of five subcoils of which the innermost is composed of two parts, A_1 and A_2, electrically in parallel (see Table 1). In the innermost coil (A_1) the maximum power density will be as much as 13 W/mm^3, and locally the conductor may heat up to 113 °C.

The design uses 'modified' cooling hole and tie-rod hole shape [2] to spread out stress and current density peaks. The coils also have an appreciable degree of vertical grading (partially to prevent the endplates to come loose when magnetic forces compress the coils, partially to increase efficiency) and modified Weggel stacking (i.e. a non-integer number of plates per turn) to reduce the slit factor for the B and C coils. When the coil proves to behave well, we will increase the margin of voltage of our power converters by adjusting the step-changer on the existing 50 kV distribution transformer in the hope to increase the available power to 40 kA × 550 V (22 MW): when operated at 40 kA the magnet will generate more than 38 T.

4 The Nijmegen 45 T Hybrid Magnet System

The core of the 45 T hybrid magnet 'system' now under development is the superconducting coil that generates the background field, and a state-of-the-art resistive coil designed to generate the highest possible magnetic field in the background field

Table 1 Design parameters of the 38 T magnet

	A_1	A_2	B	C	D	E
Inner radius (mm)	19.0	34.0	76.0	133.0	210.0	297.0
Outer radius (mm)	33.0	73.0	130.0	207.0	294.0	495.0
Length (mm)	230.4	233.0	385.6	503.8	618.9	669.3
Mass (kg)	5.2	30.4	129.9	376.2	771.9	2967
Current (kA)	11.7	27.8	39.5	39.5	39.5	39.5
Voltage drop (V)	112.4	112.4	157.8	125.4	61.6	65.3
Self field (T)	6.20	9.39	8.77	6.47	3.38	3.33
Total field	6.20	15.59	24.36	30.83	34.21	37.54

of the 'outsert'. The resistive insert magnet of the 45 T hybrid magnet system will be totally designed and built in house, and may generate 32.9 T at 39.5 kA in a 32 mm useful bore, at a power of almost 21 MW. The Nijmegen hybrid magnet will use independent current sources for the superconducting coil and the insert magnet, and will normally be operated with the superconducting magnet fully energized and varying the magnetic field of the insert magnet.

Table 2 gives some of the details of the cold mass. The Nijmegen team originally had sought collaboration with industry to design and build the superconducting magnet, but had to decide to manage the programme themselves and seek collaboration with other institutes. It was chosen to apply Cable-in-Conduit Technology with cabled Nb_3Sn strands cooled by a flow of supercritical helium, and we recently decided to employ the same cable design as our colleagues at the NHMFL [6]. With this approach, we can profit from validation tests performed in the past and from the development of the technology to manufacture such large coils. As a consequence the Nijmegen magnet, as the other magnets under construction at NHMFL, will be operated at 20 kA.

We have placed an order for the high performance Nb_3Sn strand at Oxford Superconducting Technology and will have the strand cabled and jacketed end of 2013. The NHMFL is willing to help us winding, reacting and impregnating the coil, and we will integrate the coil into a cryostat assembled in Nijmegen.

The hybrid magnet system requires a cryogenic plant including a helium liquefier and a dedicated valve box, and multiple interconnecting cryogenic lines between the several subsystems. We have chosen for a modular approach in the design.

The radiation shields in the cryostats and cryogenic lines will be cooled to 80 K by a forced flow of 20 bar helium gas using a dedicated Stirling Cryogenerator with a cooling capacity at this temperature of over 850 W. The cold helium gas produced by the Stirling Cryogenerator will also provide for the cool-down of the cold mass from room temperature.

The coil and superconducting connections, such as the high-T_c current leads, will be cooled with a flow of up to 12 g/s supercritical helium. When the system is in operation, the cold helium gas produced by the cold box is first cooled to 4.5 K through a heat-exchanger immersed in a volume of liquid helium in the valve box, then passed through the lead junctions and 18 layers of windings of the coil in parallel, returned

Table 2 Main characteristics of the superconducting coil

Central field strength	12.6 T
Current	20 kA
Superconducting strand	238 km, ≈1,000 kg

	HF	MF	LF
Cabling pattern	$3 \times 3 \times 3 \times 3 \times 4$	$\{2 \times (2 + 1\text{Cu}) + 2 \times (1 + 2\text{Cu})\} \times 4 \times 5$	$(1 + 2\text{Cu}) \times 4 \times 4 \times 4$
Number of s/c strands	324	120	64
Number of copper strands	0	120	128
Number of layers	3	3	12
Turns/layer	28	33	39
Inner radius	360 mm	409 mm	457 mm
Outer radius	409 mm	457 mm	644 mm
length	825 mm	819 mm	826 mm

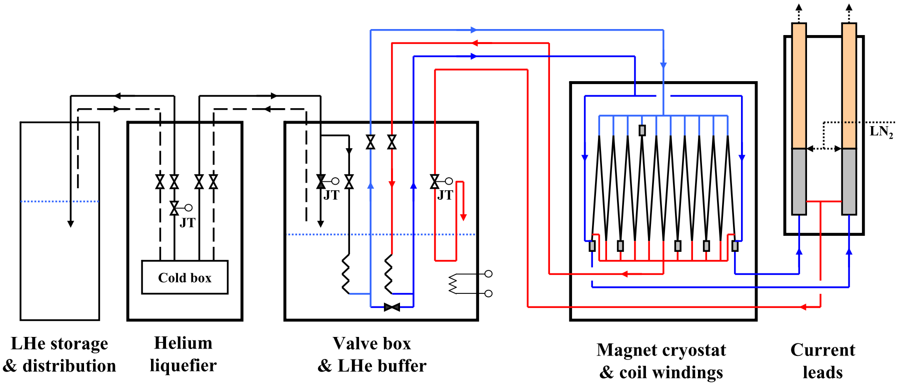

Fig. 2 Principle of the 4.5 K cooling showing *on the left* the 40 l/h helium liquefier and the liquid helium storage vessel (to serve the laboratory), and *on the right* the windings of the superconducting coil in the magnet cryostat and the connections of the different conductors used, the high-T_c current leads in their separate cryostat, and the valve box with its buffer volume of liquid helium (Color figure online)

to the valve box to be recooled to 4.5 K, and then providing the cooling for the busbar and the high-T_c current leads (see Fig. 2). Finally the helium is partly liquefied into the valve box using a Joule-Thomson valve which adjusts the pressure of the helium gas to about 6 bar.

The static heat load at 4.5 K will be 63 W, while the cold box will have a cooling capacity of more than 180 W. During ramping the superconducting coil, however, eddy current and magnetisation losses will cause an additional dynamic heat load up to 40–60 W (for charging times between 1,800 and 3,600 s), in fact at a moment when the current is still far below 20 kA. The dynamic heat load resulting from variation of the magnetic field of the insert coil during experiments is negligible. A heater in the

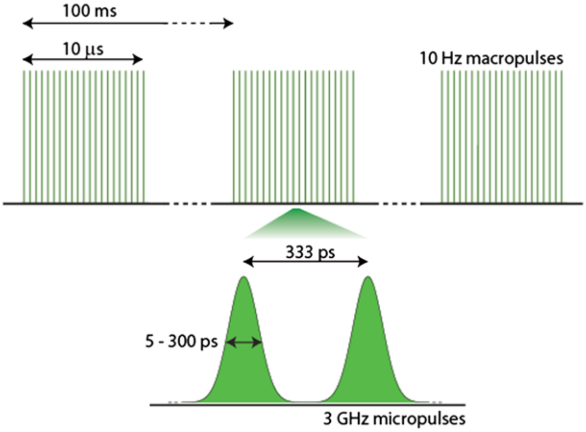

Fig. 3 Pulse structure of the Nijmegen THz-FEL. Output are 10 Hz macro-pulses of about 10 µs duration consisting of a 3 GHz pulse train of micro-pulses of 5–300 ps duration, depending on wavelength and bandwidth (Color figure online)

liquid helium reservoir is used to balance the return flow of evaporating helium gas to the flow produced by the cold box, so that in normal operation the magnet system, valve box and cold box form a closed cycle system with a constant content of helium, and the cold box does not need to take in any gas from the helium recovery system, nor return any gas.

The electrical equipment includes a 20 kA low-voltage current source, and switching gear and dump resistors to protect the magnet by extracting the magnetic energy rapidly when the need arises (e.g. a ‘quench’). Unforeseen events in the resistive coil or its 20 MW power supply may lead to critical heat load in parts of the superconducting magnet, and steps are taken to mitigate the effects so that in general not a quench will result, but a gentle dump of the superconducting magnet’s 55 MJ energy in a few seconds, with a voltage surge of less than 3 kV.

The commissioning of the new Nijmegen 45 T hybrid magnet system is foreseen for the end of 2016.

5 The Free Electron Laser FLARE

The Free Electron Laser, FLARE, built in Nijmegen is a novel light source generating powerful pulsed light in the terahertz part of the spectrum between 200 GHz ($\lambda =$ 1.5 mm) and 3 THz ($\lambda = 100$ µm).

The special feature of this laser system will be the variable and narrow bandwidth of the laser output, which allows both pump-probe and non-linear experiments as well as high quality linear spectroscopy. The specifications have been chosen primarily to make a significant step forward in material science at high (around 30 T) and very high magnetic fields (up to 45 T), resulting in a unique combination of high magnetic fields and THz spectroscopy. The light source aims at allowing saturation spectroscopy and pulse-echo experiments under these conditions. However, the specifications render this system also a very useful light source for molecular spectroscopy, material science without magnetic fields, etc. The free electron laser FLARE has produced its first light in September 2011 at a wavelength of 700 µm.

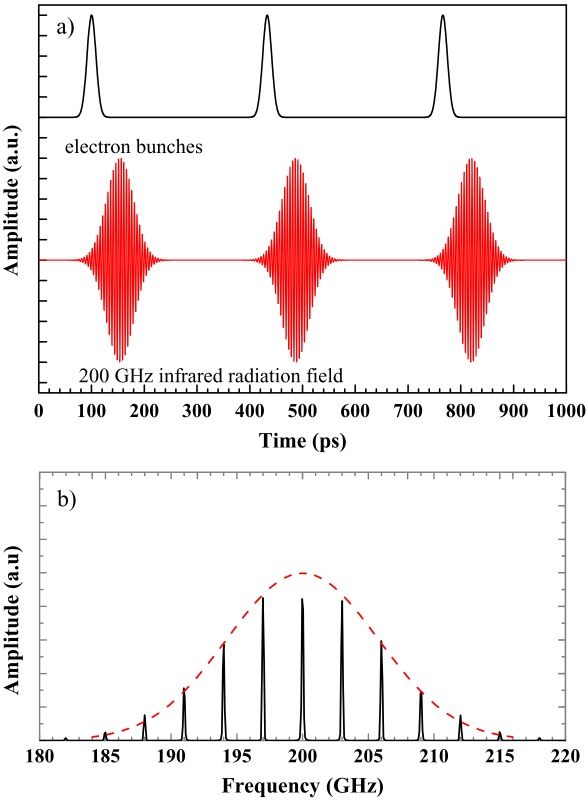

Fig. 4 The upper curve in Fig. 4a shows the regular 333 ps separation between the electron bunches, and the lower curve shows some of the few thousand of phase locked pulses of 200 GHz infrared radiation that FLARE may produce. Figure 4b sketches the effect of the frequency (power) spectrum of a sequence of many pulses. The broad bandwidth of an individual FEL pulse (*dashed curve*) translates into a frequency comb in which all frequencies are very narrow and exact multiples of the 3 GHz of the RF accelerator system (Color figure online)

Tuning has now been established with at least 1 W output power over the range of 100 to 1400 µm.

Light will be generated in two distinct modes [7]:

- The first mode, the high intensity ‘pump-probe pulse mode’, consists of trains of micro-pulses each of a length of 10 to 50 ps depending on the wavelength with a repetition rate of 3 GHz (see Fig. 3). The maximum power in the micro-pulses exceeds 100 kW, with typically 3 µJ per micro-pulse. The pulse train forms a macro-pulse of 10 µs. Selection of single micro-pulses or a small number of micro-pulses is possible.
- The second mode, the ‘spectroscopic mode’, consists of narrow bandwidth radiation ($\Delta\lambda/\lambda < 1 \times 10^{-5}$) in the form of long pulses of 6 to 10 µs duration with an estimated power of 100 W.

The macro-pulse repetition frequency of the laser is 10 Hz.

The length of a light pulse generated in a FEL and hence its wavelength accuracy and bandwidth are related to the number (N) of undulator periods and the detuning of the optical cavity. The undulator of our FEL has 40 periods, and then a bandwidth ($\Delta\lambda/\lambda$) of 2 % down to 0.5 % may be reached. The 0.5 % requires an optical system that has sufficient gain. The resulting resolving power of the laser is however insufficient for the aims of the Nijmegen FEL. The time structure of the pulses formed are bandwidth limited, and this implies, for our wavelength region of 100 µm to 1.5 mm and using a 2 % bandwidth, a pulse lengths of 15 to 200 ps.

Obviously, the generation of pulses of high optical resolution with a 2×10^{-5} bandwidth requires stretching the pulses to lengths of 15 ns (at 100 µm) and 200 ns (at 1.5 mm). The mechanism to achieve this bandwidth effectively is the generation of a so-called frequency comb, with a relatively large mode spacing. A frequency-comb implies that only sharply defined frequencies with regular spacing are present in the frequency spectrum. This output is the logic and necessary consequence of a train of identical pulses. Figure 4 shows both the time structure of the series of micro-pulses as well as the frequency spectrum when analyzing the frequency components of the whole train of micro-pulses, assuming that all micro-pulses have an identical phase.

One observes very sharp frequency spikes separated by the repetition frequency of the accelerator system. The wavelengths of the wavelength fringes are given by $\lambda_{\text{fringe}} = cn/\nu_{\text{acc}}$, with n an integer and ν_{acc} the repetition frequency of the accelerator system. Hence by ensuring an exact phase relation between all micro-pulses, the lasing power concentrates in a small number of narrow modes. The output of the FEL will be equipped with an etalon in order to filter out one of the required modes, with some but not a dramatic reduction in power. This mechanism has been shown to work at FELIX in Rijnhuizen [8].

6 The FELIX Facility

Sofar, we have described the details of FLARE, a new FEL that operates in the far-infrared or terahertz part of the frequency range. In the Netherlands, a successful radiation facility exists in the FOM-Institute Rijnhuizen. Based on one electron source, it offers three beam lines, of which two, FEL-1, and FEL-2, cover the wavelength range from 3 to 150 µm. The third beam line is called FELICE and has been constructed such that experiments can be done within the optical FEL cavity. This beam line covers the short wavelength part of the frequency range. FELIX Rijnhuizen has operated as an open access facility for 15 years and has made ground breaking contributions to the spectroscopy and structure determination of clusters, biomolecules, and ions.

It was decided to move these FEL's and the staff to the Radboud University Nijmegen. An overview of the lasers as they will be placed in the vault at the RU is shown in Fig. 5. The installation in Nijmegen gives another expansion of the capabilities of the HFML. The move is taking place in 2012 and requires the expansion of the dedicated laboratory building. Facility operation including the optical connection between the radiation facility and the high field magnets is planned to start in the second half of 2013.

The output of the FEL's consists of bursts of intense, ultrashort electromagnetic pulses, which are bandwidth limited. The output of the FELIX facility in the past clearly shows what the strength is of FEL's for research in the natural sciences. The high fluence of the bursts (of the order of 30–100 mJ per macro-pulse for FELIX-I, FELIX-II, and FLARE) makes it possible to make even individual molecules absorb multiple photons during a burst. In individual clusters or biomolecules these many FIR photons enter the molecule through a specific door-way excitation. The effect

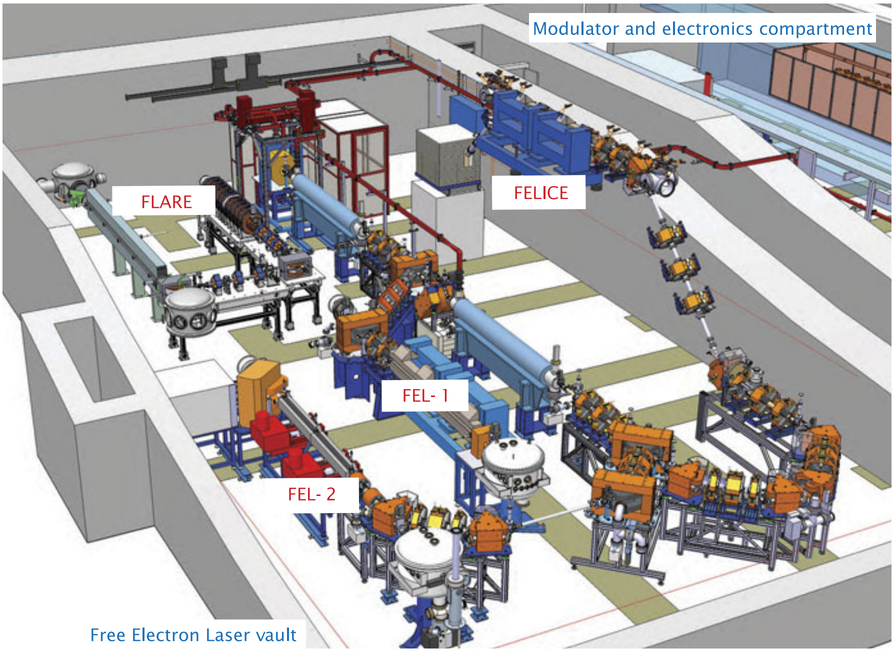

Fig. 5 The FELIX facility houses the lasers FLARE (100–1500 µm), FEL-1 (20–150 µm), FEL-2 (3–45 µm) and FELICE (5–100 µm). The infrared radiation of FLARE and FELIX is led via separate optical beamlines to the different user stations, FELICE allows intracavity measurements and the *optical cavity* extends into the laboratory above the FEL vault (Color figure online)

of the multiple photon absorption is significant heating of each molecule resulting in changes such as fragmentation or ionization. By recording at which FIR wavelengths a molecular change is observed one obtains effectively a FIR absorption spectrum. This technique is an example of action spectroscopy. In fullerenes, C_{60}, it has been observed that more than 1,000 photons were absorbed in a single FEL burst. The high fluence creates also a relatively large probability of photon absorption in systems with smaller FIR absorption cross section.

By combining FEL output with that of visible or UV lasers, one can perform another form of action spectroscopy. Here a UV laser is fixed at a wavelength at which non-excited ground state molecules are ionized in a multi-photon process. When the FEL wavelength equals a FIR resonance, ground state molecules are excited resulting in a decrease of the number in the ground state, and as a consequence the ionization signal by the visible/UV ionizing laser will decrease. The so-called ion dips together form a FIR absorption spectrum. These two forms of action spectroscopy describe a large fraction of the experiments that provided spectral information of molecules, clusters and molecular ions. In combination with quantum chemistry predictions of the FIR response of the clusters and molecules, the FIR spectra allow to confirm unique structure information that cannot be obtained in any other way. The high fluence of the FEL's is also well suited where saturation spectroscopy is required such as in solid state physics and semi-conductor research.

7 Conclusions

The HFML is rapidly developing its full potential and can offer users an increasing amount of access for their experiments. In the near future the HFML will have the highest steady magnetic fields available anywhere. The HFML is closely collaborating with the Laboratoire National des Champs Magnétiques Intenses in Grenoble (LNCMI-G) and with the pulsed field installations in Dresden (Hochfeld-Magnetlabor Dresden, HLD) and Toulouse (LNCMI-T), in the European funded EuroMagNET and EMFL projects. Users are encouraged to submit their proposals for the user selection process of the EuroMagNET/EMFL collaboration at any of the two calls in April and October each year.

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