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High Field Laboratory Dresden (HLD)

Note:

This statement given by a subgroup of the steering committee „Large research facilities for basic research" of the German Science Council concentrates on the scientific and technical investigation of the project. The statement if the project should be funded or not is given by the Science Council itself by a final evaluation of all nine projects. This statement is given in a seperate report.

A. Introduction and Background

A. I Field of Research

Magnetism is a fundamental feature of all materials, including those that are conventionally considered to be non-magnetic. In very high magnetic fields, in the range well above 10 Tesla the magnetic interaction gradually becomes significant in all materials even at ordinary temperatures, and above 100 Tesla the electronic states in matter start to become seriously modified. Thus the magnetic field is one of the fundamental thermodynamic parameters, just like temperature and pressure, which are capable of changing the physical, chemical, mechanical and other properties of matter.

The study of the response of a material to the applied magnetic field allows for investigations of phase equilibria and transformations. This is of special importance when considering collective electronic behaviour, where the ability to tune the ground states is crucial to understand the balance of interacting factors that determine the macroscopic properties. The magnetic field influences the spin of particles, produces an additional force (Lorentz-force) on moving charged particles, changes the density of electronic states and quantizes the energy. Due to its fundamental importance in nature and its significant influence on the state of matter, the magnetic field is of interest in a wide variety of scientific disciplines like semiconductor physics, the broad field of magnetism and metals, strongly correlated electron systems, chemistry, spin chemistry, complex fluids, life sciences, biology, biotechnology, medicine, magnetic resonance and optical spectroscopy.

Research using high magnetic fields has been particularly successful during the last twenty years and has led to important discoveries. In 1980 the Quantum Hall Effect (QHE) was discovered at the High Magnetic Field Laboratory (HMFL) Grenoble by Klaus von Klitzing who received the Nobel prize in 1985. At the HMFL the QHE constant could be derived from natural constants and measured with high precision. Now the quantized Hall resistance serves as a resistance standard in the international system of units. Furthermore, the discovery of the QHE resulted in new phenomena such as the Wigner-crystallization and the Fractional Quantum Hall Effect (FQHE) which was honoured with the Nobel prize in 1998. The discovery of the FQHE by Horst Störmer and Daniel C. Tsui and its theoretical explanation by Robert B. Laughlin includes the idea that interacting electrons in a high magnetic field form a novel type of quasi-particles whose charge is a rational fraction of the elementary charge. This discovery was only possible by the access to high magnetic fields since neither the integer nor the FQHE had been predicted or expected by theory. Also, high magnetic fields have played an important role in the rapid development of semiconductors and have substantially contributed to the development of microelectronics and nanotechnology.

Concerning the development of high magnetic field technology the present state of the art in Europe includes static fields (DC) up to 30 Tesla and pulsed fields up to about 60 Tesla with pulse lengths of 10 – 20 ms. At the moment a substantial number of laboratories provide pulsed or static fields, some of them making efforts to extend the limits of current technology and to enhance the accessible fields. Facilities in the USA, Japan, France and The Netherlands are the world-wide leading laboratories, especially in DC fields.

The following table gives an overview on leading high magnetic field laboratories that provide pulsed fields of 50 Tesla and more:

Site	**Present max. field parameters (field/bore/pulse)**			**Prospective max. field parameters (field/bore/pulse)**		
Leuven (Belgium)	60 Tesla	20 mm	20 ms			
Nijmegen (Netherlands)				80 Tesla	23 mm	5ms
Toulouse (France)	61 Tesla	11 mm	27 ms	80 Tesla	15 mm	10 ms
Dresden (Germany)	52 Tesla	24 mm	10 ms	100 Tesla 60 Tesla	20 mm 50mm	10-20 ms 1.000 ms
HU Berlin (Germany)	62 Tesla	18 mm	10 ms			
University of Frankfurt (Germany)	50 Tesla	24 mm	20 ms			
NRIM, Tsukuba (Japan)	73 Tesla	10 mm	3 ms	80 Tesla	20 mm	60 ms
NHMFL Talla./Los Alamos (USA)	50 Tesla 60 Tesla	24 mm 32 mm	20 ms 100 ms	100 Tesla 60 Tesla	24 mm 32 mm	20 ms 1000 ms
Osaka University (Japan)	80 Tesla	10 mm	25 ms			

The following table lists leading high magnetic field laboratories that provide DC fields:

Site	Power supply	Present max. Field	Prospective max. Field
NHMFL, Talla./Los Alamos (USA)	40 MW	33-45 Tesla	
HMFL, Grenoble (France)	24 MW	31 Tesla	40 Tesla
HMFL, Nijmegen (Netherlands)	6 MW (20 MW under construction)	20 Tesla	40 Tesla
NRIM, Tsukuba (Japan)	15 MW	37 Tesla	

There is a world-wide consensus that much higher magnetic fields than presently accessible would be needed in the near future to foster new scientific challenges. For instance, semiconductor physicists see a clear need for magnetic fields well in excess of 50 Tesla to explore the new physics associated with new materials and structures processed on the nanometer scale. The availability of these high fields will both, open up new possibilities in fundamental research on quantum liquids in semiconductors (such as in the FQHE) and will be of great assistance in the characterization, further development and exploitation of novel semiconductor materials.

German research with high magnetic fields is world-leading in many fields. This is well documented by the Nobel prize discovery of the QHE and by other top results as, for example, the discovery of Heavy Fermion superconductivity or important contributions to correlated electronic systems as well as by high-end sample preparation for the FQHE.

German scientists of the Max Planck Institute for Solid State Research Stuttgart are currently involved in running the HMFL in Grenoble. However, this participation will be finished in 2004. According to the applicants, in Germany there is a fundamental deficit in access to high magnetic field facilities. Compared to the Netherlands and France the availability of high-field facilities for German researchers is much more limited.

Facing the fact that the USA has taken the lead in the development of high magnetic field technology an ESF report on the scientific case for developing high field magnets already argued in 1998 that there is a strong need for both static fields up to 50 Tesla and long pulsed fields up to 100 Tesla.[1]

While in the USA a 100 Tesla pulsed field installation is under construction at the NHMFL and will be put into operation possibly in 2003, there are three projects in Europe that aim at higher pulsed fields. However, the HMFL Toulouse and possibly the HMFL Nijmegen are planning a 80 Tesla facility with short pulses while the Dresden proposal aims at 100 Tesla. The facility that is proposed by the Hahn-Meitner-Institute (HMI) is planned to provide DC fields of up to 35 to 40 Tesla (see introduction and background on the High Magnetic Field Facility for Neutron Scattering Research).

A.II The Proposed Facility

II.1 Scientific Objectives and Research Prospects

The proposed High Field Laboratory Dresden (HLD) is planned to be built at the Forschungszentrum Rossendorf (FZR) and will be capable of obtaining magnetic fields up to 100 Tesla with 10 ms pulse duration. The HLD will provide non-destructive pulsed magnetic fields using three types of magnets with different maximum field, pulse time, and bore diameters:

	Magnet A	Magnet B	Magnet C
Maximum field	100 Tesla	70 Tesla	60 Tesla
Pulse duration	10 – 20 ms	100 – 200 ms	1000 ms
Diameter of sample space	20 mm	24 mm	50 mm

Thus, the proposed facility will significantly enhance the magnetic field strength of typically 60 Tesla so far provided at world-wide leading non-destructive high field facilities.

The proposed facility will provide access to the energy range of the infrared free electron laser (FEL) currently being under construction at the radiation source ELBE

[1] ESF: The scientific case for a European Laboratory for 100 Tesla Science. November 1998, p. 10.

at FZR. The envisaged combination of HLD and FEL was already appreciated by the Wissenschaftsrat in 2000 since it would provide new and world-wide unique possibilities in High Field-Infrared-Spectroscopy.[2]

II.1.1 Research Program

Research at the HLD is planned to be centred in material science and solid state physics, focusing either on new effects, new materials or new techniques. Apart from being open to all qualified users, the laboratory will have an extensive in-house research program in high magnetic fields. The following research program is planned to be mainly investigated by scientists of five institutions in Dresden (see A.III).

Semicondutors and low dimensional structures

High magnetic fields force conducting electrons into discrete states (Landau-levels) with corresponding cyclotron energies. Transitions between Landau-levels induced by electromagnetic radiation (cyclotron resonance) provide important information on electron energy states, effective masses, and scattering times, derived, e.g. from interactions with phonons or impurities. In magnetic fields as high as 100 Tesla the cyclotron radius (2.5 nm) is reduced to values closer to the atomic scale, thus having significant effects on the band structure. Cyclotron energies beyond 50 meV will open up a new regime for the study of electron-phonon interaction in cyclotron resonance and magneto-phonon resonance experiments.

In many semiconductors optical transitions between cyclotron states in fields between 50 and 100 Tesla occur at wavelengths in the mid- to far-infrared region (10-100 μm). Due to the lack of tunable laser sources in this region, pulsed-field experiments have so far been possible only at a few, fixed wavelengths. The FEL for mid and far infrared radiation currently under construction at the FZR will permit experiments at continuously tunable wavelengths between 5 μm and 150 μm. Together with a high field laboratory, this would provide a world-wide unique facility for experiments combining high quality radiation of the FEL (pulse length, repetition rate, intensity, two-colour experiments) with magnetic fields up to 100 Tesla. In

[2] Wissenschaftsrat: Stellungnahme zum Forschungszentrum Rossendorf (FZR). 2000, p. 102.

particular, the high repetition rate of 1.3 MHz will permit the recording of hundred thousand data points in one 10 ms magnetic field shot. In magnetic fields of 100 Tesla, also the electron spin resonance energy for materials with a low g-factor is pushed into the THz regime and can thus be investigated with the FEL.

Other research activities at the HLD will be related to the magnetic-field induced metal-insulator transition in semiconductor superlattices, which will be studied using a combination of transport and infrared experiments. Higher magnetic fields will permit the investigation of more heavily doped samples, where qualitatively different behaviour may be expected. Theoretical predictions have recently been made on the infrared response of quantum dot arrays in magnetic fields.

In general, spectroscopy of both narrow- and wide-gap semiconductors are expected to benefit from higher magnetic fields. In narrow-gap semiconductors with their small effective mass, the cyclotron energy could exceed the band gap and thus virtually destroy the usual band structure. In wide-gap semiconductors that become more and more technologically important high fields are crucial to obtain a thorough understanding of the band structure. The same is true for all materials with high effective masses or low carrier mobilities, such as heavily doped systems, or substances which cannot be produced with high purity. All these materials require very high magnetic fields to resolve Landau levels, i.e. to make possible measurements of magnetic quantum oscillations (Shubnikov- de Haas and de Haas – van Alphen effect) or cyclotron resonance.

Magnetism and metal physics

The high coercitivity of a permanent magnetic material relies on the large magnetic anisotropy associated with the rare earth 4f crystal field. This is transferred to Fe moments via 4f-3d exchange interaction. An applied pulsed field of 100 Tesla would increase the number of field-induced re-orientations of the rare-earth and transition metal moments. This will lead to important new information concerning both the anisotropy, the underlying 4f crystal field parameters, and the 4f-3d interaction. Some of the intermetallic compounds of 4f-rare earth elements and 3d-transitional metals show metamagnetic transitions in high magnetic fields, for other substances theoretical calculations propose such transitions. The magnetism of the materials can be explained by crystal field effects and exchange interactions (bilinear, biquadratic or multipolar; isotropic: Heisenberg, RKKY or anisotropic). At the Institute for Applied Physics at the Dresden University of Technology the computer program “McPHASE” has been developed to simulate and analyse high field experiments. Measurements are planned for RCo_2, RCo_3 and R_2Fe_{17}, R_2Co_{17}, which are relevant for applications as permanent magnet. A number of those materials could not magnetically be saturated in fields as large as 52 Tesla, a phenomenon not yet understood.

Further experiments designed by the Institute for Applied Physics at the Dresden University of Technology will be focused on irreversible, magnetically induced structural transitions in rare earth intermetallics. An example for these effects is the “axis conversion” in antiferromagnetically ordered RCu_2 and related compounds. An applied magnetic field can increase the lattice symmetry. The transition remains stable even after switching off the field. Most of these transitions were first detected in high fields; therefore it is necessary to study different compounds in pulsed high magnetic fields. Some of the compounds are promising candidates for applications (there are relations to “shape memory alloys”). The experiments use magnetisation and resistivity measurements as well as magnetostriction measurements by capacitive dilatometry.

It is also intended to perform experiments in cooperation with the Technical University Vienna on exchange coupled magnets characterized by magnetic interaction across grain boundaries as a result of nanocrystaline structure. Much of experimental work at fields up to 100 Tesla on nanocrystaline model substances is essential to understand the nature of this exchange coupled magnetism and ultimately to improve the properties of this kind of magnets.

The Technical University Vienna proposed further experiments with an application oriented focus: It could be tried to replace high mechanical pressure necessary in the production process of permanent magnets to align the magnetic moments by high magnetic fields. Another more applied experiment aims at deep-drawing of sheet metal in pulsed high fields. These as well as other experiments promise interesting technical applications for the high field facility.

Dresden groups plan to perform high field magnetization measurements on novel materials like the organic weakly ferromagnetic substance TDAE-C_{60} or low-dimensional copper oxides. Especially the information on spin-gaps, metamagnetic transitions and transport properties at high magnetic fields are of importance in these systems. One dimensional electron systems in nitride-compounds also represent a group of materials with interesting features when exposed to high magnetic fields. The crystal structure and first calculations support speculations that transitions between one-dimensional metals and localized electrons can be observed and investigated in high magnetic fields. Scientist at the new Max-Planck Institutes in Dresden intend to work in this field using high magnetic fields.

Magnetoelectrical transport phenomena (magnetoresistance, Hall effect, giant, colossal and tunneling magnetoresistance etc.) connected with certain field-induced changes or with certain microstructures are to be investigated in a broader range of magnetic field than presently available. In this respect some predictions have been made by theoretical physicists working in Dresden.

Doped oxides are another group of materials for high field experiments. These systems are ferromagnetic metals, owing to the double exchange process, but the carriers become localized in an insulating state above the Curie temperature T_c. An applied magnetic field effectively raises T_c so that at a temperature near T_c the system is shifted towards the metallic state. Structural transformations and further shifts of T_c are expected in response to high magnetic fields up to 100 Tesla.

Heavy-fermion, i.e. certain rare-earth- or actinide-based, compounds are systems which are close to a magnetic instability. Below a certain ("Kondo") temperature, their susceptibility becomes temperature independent (Pauli-like) and their charge carriers get very large effective masses (up to 1000 times the free-electron mass) screening localized magnetic moments. Some of these heavy-fermion metals become superconducting at even lower temperatures. Applied magnetic fields in the range of

10 to 100 Tesla are able to suppress these novel states because of the low characteristic energy scale which results from the competition between the strong local Coulomb repulsion among the f-electrons and the weak hybridisation of f-electrons with s-, p- or d- conduction electrons ("Kondo effect"). This is shown by a dramatic decrease of the effective electron mass with raising magnetic field. The suppression of the Kondo effect by magnetic fields reveals information on the origin of the large electron masses. Kondo effect and heavy-fermion metals belong to the currently most active research topics in solid-state physics. Further experiments in high fields, e.g. de Haas-van Alphen experiments, are necessary to arrive at a detailed understanding of these phenomena in the real materials.

So-called "Kondo insulators" are semiconductors/semimetals with extremely narrow (pseudo) gaps, typically 1 – 10 meV. At correspondingly high temperatures they are behaving like dirty intermediate-valence metals. Application of high magnetic fields may destroy the "Kondo insulating" state as has, in fact, been demonstrated by the LANL group for $Ce_3Bi_4Pt_3$. Here, the field necessary to induce the semiconducting to metal transition was about 50 Tesla. In Dresden it is planned to study prototypical "Kondo-insulators" like CeNiSn, $Ce_3Sb_4Au_3$, $CeSb_4Pt_3$, YbB_{12}, SmB_6 and FeSi. Conductivity, magnetization and susceptibility measurements are to be performed to clarify the nature of the energy gap. Of special interest is the question whether the disappearance of the energy gap occurs continuously or in jumps. According investigations of YbB_{12} require magnetic fields of 55 Tesla, for systems with a larger energy gap accordingly higher fields are necessary.

An intensive search for new "Kondo insulators" has been initiated by chemists and physicists of the Max Planck Institute for Chemical Physics of Solids Dresden. Here, filled-cage materials, i.e. so-called clathrate compounds are of particular interest because they are promising candidates for their application in Peltier refrigerators to reach very low temperatures (in the range of 30 K) - starting at a base temperature of 77 K. This would allow to apply superconducting technologies utilizing high T_C-superconducting materials – without the need to use liquid He as the cooling agent.

Experiments are planned with 5f compounds, 4f-systems as well as 3d-systems like in order to study metamagnetic phase transitions which often occur in heavy-fermion compounds at high magnetic fields. Thereby it is of fundamental interest which microscopic changes take place in the electronic system and how the Fermi surfaces and effective masses of the quasiparticles are modified. It is to be clarified whether or not general differences exist between Yb-, Ce-, U- and transition-metal-systems which might be expected due to the different localization of their electronic wave functions. In this respect, high magnetic fields are required to allow determining effective masses beyond the metamagnetic transition.

Furthermore Dresden’s physicists plan experiments on the 4f and 5f compounds which show an ordered quadrupole state at low temperature. Measurements of high-field susceptibility, magnetostriction and magnetoresistance shall reveal how the order of quadrupole and higher multipole moments can be proved, why the ordering temperature often raises with increasing magnetic field and at which field level the critical field curves reappear to be normal.

Some organic materials also show unusual magnetic properties and shall be subjected to high-field experiments. For example, some charge transfer salts can be “simple metallic”, “superconducting” or “metallic and magnetic”. The B-T-phase diagrams seem to be very complex and are far from being understood. Measurements of magnetization, magnetostriction and the de Haas-van Alphen effect are intended in Dresden and expected to reveal important information on the nature of magnetism in these systems.

Superconductivity

Within the field of superconductivity the high-temperature (HT_c-)superconductivity is the most topical and at the same time the least understood phenomenon. HT_c-superconductors are characterized by high critical temperatures of superconducting phase transitions (up to about 140 K) and by high critical magnetic fields exceeding even 100 Tesla. These parameters make HT_c-superconductors promising candidates for many technical applications. Apart from a successful materials research in this field, there are many open questions regarding the microscopic mechanism of HT_c-

superconductivity which can only be solved by investigating these substances in their normal-conducting state. Therefore it is necessary to suppress the superconducting state by applying magnetic fields higher than the critical magnetic field of the superconductor. For example, superconductivity of $La_{2-x}Sr_xCuO_4$ has been suppressed by an applied field of 70 Tesla. At low temperatures, the normal conductivity is characterized by a logarithmic singularity and by a quantum-critical point at x = 0.15. These important results for the normal-conducting state urgently have to be confirmed by the investigation of similar systems. In this field the Dresden group plans to perform experiments on numerous compounds of the class of low-dimensional cuprates which have higher critical fields. Furthermore, at these systems the temperature dependence of transport properties as Hall effect and magneto-resistance are to be investigated at high magnetic fields. With regard to applications, the determination of the upper critical magnetic field B_{c2} in these systems is of particular relevance. Corresponding investigations planned by the Dresden group require the application of high magnetic fields exceeding the presently accessible fields.

The temperature-dependence of the critical magnetic field at which superconductivity is suppressed has to be investigated in a wide range of magnetic fields in order to come to a better understanding of HT_c-superconductivity. Differing from theoretical predictions, an extremely large increase of the upper critical field of $Bi_2Sr_2CuO_{6-\delta}$ has been found up to values of 28 Tesla without any signs of saturation towards zero temperature. In contrast to that, $Nd_{2-x}Ce_xCuO_4$ with nearly the same critical temperature (T_c = 20 K) shows only a weak increase of the critical field up to 6 Tesla when the temperature decreases. The most important superconductors for technical application have significantly higher T_c-values. The corresponding critical fields are partly much larger than those presently available at leading facilities.

A further topic of scientific interest particularly with respect to the electronic structure of HT_c-superconductors is the oscillation of magnetization (de Haas-van Alphen effect) in magnetic fields higher than their critical field. High-field experiments are also planned to investigate the flux pinning at high magnetic fields which is of significance for the use of superconductors as permanent magnets. The maintenance of flux pinning in superconducting magnets even at highest fields is a prerequisite for their practical application. Materials research on the cuprates, in particular on the pinning, also provides the basis for the next generation of superconducting coils applied for the provision of static magnetic fields higher than 20 Tesla.

The scientific high field program of the Dresden group also includes the search for the state of field-induced (triplet-)superconductivity which, although predicted by theory, has not yet been observed. Also, field-induced superconductivity through compensation of inner fields by high applied fields (Jaccarino-Peter effect) has only been found for a single substance until now.

Complex liquids, chemistry, biology

Complex liquids show a manifold of responses when subjected to high magnetic fields. Such magneto-mechanical effects include the orientation of molecules, polymers, liquid crystals, membranes and ordered supra-molecular structures due to the anisotropy of their diamagnetic or paramagnetic susceptibilities. The field induced molecular alignment is most sensitively detected by the induced optical birefringence. This technique, known as Cotton-Mouton effect would greatly benefit from high fields, as its resolution increases with B^2. Such increase would allow the exploration of inherently thin samples, weakly anisotropic molecules and substantially smaller concentrations or smaller sample volumes, thus allowing the study of biological samples difficult to prepare in required quantities.

An applied magnetic field can shift the reaction equilibrium between substances with different magnetic moments. Being relatively small at low magnetic fields this effect, also increasing proportional to B^2, can reach values of some percents at 100 Tesla. This opens a new field of “magnetic chemistry”. Magnetic interactions that are small compared to thermal energies at usual temperatures (>200 K), and even much smaller than reaction energies of the chemical transformations, can be used to switch reaction probabilities and to control the flow into various reaction channels. Most spin chemistry experiments require the radiation of electromagnetic energy to induce or to investigate reactions. The FEL for the far infrared presently under construction at the

FZR will be of great advantage in this kind of experiments, because many spin transitions correspond to the wavelength range of the new laser.

In the field of biology magnetic fields are of importance, too. The object of life science in this area is to determine the biological effects of magnetic fields on living organisms. This is a very broad area encompassing the use that species make of the earth's magnetic field for orientation, the application of magnetic fields for medical diagnosis and the studies of health risks run by exposure to high fields in various environments.

Biological substances are mostly diamagnetic. Therefore the main effect of magnetic fields on biological matter consists of magnetic alignment as a result of diamagnetic anisotropy of bondings and molecules. As the extent of alignment increases proportionally to B^2 one can expect a complete alignment of e.g. viruses and chromosomes at magnetic fields as high as 100 Tesla.

II.1.2 National/international networks

The proposal of HLD was worked out by five research institutes located at Dresden (see A. III) that will jointly act in the realization of the project as well as in the operation of the facility.

On the national scale the project is embedded in well-established networks like the Materialforschungsverbund Dresden and into joint projects such as Special Research Programs of the Deutsche Forschungsgemeinschaft (DFG), SFB 463 “Rare earth – transition metal compounds: Structure, magnetism and transport” and the newly established SFB 609 “Electrodynomic flux manipulation in metallurgy, crystal growth and electrochemistry”. Recently, the participation of Dresden’s scientists in biotechnological research and development has been significantly increased. This has been achieved by the new Max-Planck Institute for Molecular Cell Biology and Genetics in Dresden and by the joint initiatives “BioMeT” and “Molecular Bioengineering” launched by a group of Dresden institutes.

The Dresden group is involved in the EU High Field Infrastructure Cooperative Network which gathers European forces to build non-destructive pulsed high field magnets. Bilateral agreements of co-operation with the world-wide leading high field laboratory NHMFL Tallahassee/Los Alamos are maintained. Another formal agreement of co-operation is in preparation between the Dresden high field group, the high field laboratory in Nijmegen and the high field laboratory in Toulouse. Also, the applicants intend to apply for the acknowledgement of the proposed HLD as a European Large Scale Facility which would further strengthen the co-operation with the international high field community.

Strong co-operative relations are fostered with partners in Germany, Austria, Poland, and Czechia who welcome the Dresden initiative and are interested to become associated members in the planned HLD.

In case the proposal of the HMI Berlin for a static high field laboratory and the Dresden proposal for a pulsed high field laboratory would be accepted the applicants propose to establish a national Advisory Committee (see also the equivalent chapter on the High Magnetic Field Laboratory for Neutron Scattering Research).

II.2 Technology

For gaining experience in the construction and operation of pulsed magnets, a smaller pulsed field test laboratory was established in 1999 at the Institute for Solid State Physics and Materials Research Dresden (IFW). The laboratory includes pulse magnets with peak fields up to 50 Tesla in a 24 mm bore and a pulse length of about 11 ms as well as a 40 Tesla long pulse magnet with a 24 mm bore an a pulse length of about 130 ms. The coils are energized by a 1 MJ, 10 KV capacitor bank with thyrister switches. The bank is subdivided into four identical and independent units. A particular advantage is the possibility to reverse the polarity of the magnetic field pulse by means of a novel circuit with industrial circuit breakers.

Concerning the realization of the proposed HLD there are several aspects that are technically challenging:

Conductor materials for the high filed coils

The peak magnetic field of pulsed coils depends on the strength of the materials used in the coil construction, while the pulse duration depends primarily on the electrical conductivity and the volume fraction of conductor in the coil. At the envisaged field level of 100 Tesla the magnetic tension amounts up to 5 GPa, mainly taken up by the reinforcement. The conducting wires have to endure 1.3 GPa. That makes the materials development a crucial point in the realization of pulsed magnetic fields as high as 100 Tesla. IFW's recent results on microcomposite Cu-Ag alloys and steel-copper macrocomposites with perlitic steel and high-nitrogen steel meet the requirements in strength (up to 1.3 GPa) and conductivity (up to 50% of pure Cu) for 100 Tesla pulsed magnet coils.

Power supply

A further technological problem to be solved is the power supply. Huge amounts of energy have to be transferred to the high field magnet in a very short period of time. The FZR has developed and taken out a patent for a new 1 MJ modular capacitor bank which is best suited for energy storage in pulsed high field installations. One of these 1 MJ modules is already in operation at the 60 Tesla pulsed high field test facility at the IFW Dresden. Several of these modules will be combined to make the power supply for the 100 Tesla laboratory.

Measurement facilities

For precise magnetization measurements a novel pick-up coil system was designed for reduced influence of sample displacement on the measured signal. Now this system has to be improved concerning the signal/noise ratio which is small due to noise arising from the field pulse. For resistivity measurements the main activities are being focused on the improvement of the signal/noise ratio by a short-time enhancement of the current during the field pulse and by modification of the hardware.

100 Tesla is the present technological limit for non-destructive fields. The limitation for upgrading beyond 100 Tesla is determined by the properties of the materials available for coil wires. The 100 Tesla limit could only be exceeded if material with even higher strength at comparable conductivity could be developed. Substantial upgrading and expansion might be necessary in the course of 10-15 years. Generally, upgrading and enlargement is possible because of the modular construction and the availability of unobstructed space at the FZR.

The total period of operation without any further expansion would probably be 10-15 years.

II.3 Transfer of Research Results

The application of magnetic fields has significantly influenced the development of a wide range of materials and devices, thus, it is expected that the HLD will contribute to leading edge technology, especially in the fields

- magnetic materials
- ultra-strong conductor materials
- magnetisation technology

- high field technology
- superconductors for permanent magnets and energy transports,
- development of semiconductors
- pulsed and short-time measurement technology.

Material development is a crucial point in the realization of pulsed magnetic fields as high as 100 Tesla. The implementation of these results into the production of ultra-strong, highly conductive wires are expected to open up a new business field. Ultra-strong conducting materials are required in a wide range of applications where mechanical strength and electrical conductivity are of equal importance. Therefore it is intended to establish and support the production of coil wires in a regional start-up company as soon as the technology is developed.

Appropriate transfer mechanisms are practiced at the five institutes involved in the proposal. In particular the FZR and the IFW act within their specific fields at the hole range from studying fundamentals to developing applications. Scientist at these institutes are used to address their results not only to the scientific community but also to companies and industrial partners, e.g. they co-operate with Technology Transfer Centers in Dresden. From the pilot 60 Tesla project, two patents have already evolved. Also, the IFW is involved in several joint projects aiming at the implementation of superconcucting permanent magnets into products, for example in levitation technology.

A.III The Institutions Participating in the Project

The FZR was evaluated by the Wissenschaftsrat in 2000.[3] The results in application-oriented research (nuclear physics, material science, life sciences, environmental and safety research) carried out at this institution were judged to be high-level.

The FZR has contributed its experience in designing and constructing power supply systems to the proposal. The 60 Tesla test facility has been equipped with a innovative modular 1MJ capacitor bank developed and patented by the FZR and the

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[3] See footnote 2, p. 103.

IFW. The power supply of the proposed 100 Tesla facility will consist of such capacitor modules. Another field of specific competence contributed by the FZR is the computer simulation for coil design. The FZR is now preparing the site decision of the laboratory, its design as well as for negotiations with the building contractor. It is also considering details of combination of the high field laboratory with the FEL for the high field infrared spectroscopy.

The Institute for Solid State and Materials Research Dresden (IFW) was also evaluated by the Wissenschaftsrat in 2000. The wide range of research including fundamental research as well as application-oriented research was appreciated. The IFW was judged to have substantial potential for development and was also appreciated for its internationally acknowledged position.[4]

The IFW points to its long standing experience regarding materials development for ultra-strong conductors necessary for high magnetic field coils. Internationally acknowledged results have been achieved for metal matrix-composites (MMCs) and for high-T_c superconductors. Expertise and facilities for the mechanical, electrical, and structural characterization of conductors during all production steps are available at the IFW Dresden. In addition, there is significant experience in measurements of physical properties in high magnetic fields. Since the 60 Tesla test laboratory has been installed at the IFW Dresden the institute gained substantial experience in designing, constructing and running a high field facility. Presently the IFW is engaged in optimizing and up-scaling the pilot installation.

The Max Planck Institute for Chemical Physics of Solids (MPI-CPfS) is in general devoted to finding new materials, their synthesis, the growth of high-quality single crystals and the modification of their properties. These systems are investigated by means of a wide range of experiments under extreme conditions, i.e. low temperatures, high-magnetic fields and high pressures. The profound experience of the MPI-CPfS in the design and use of experimental settings will continue to play an important role in the realization of the proposed project.

The Max Planck Institute for Physics of Complex Systems (MPI-PKS) is an institute for theoretical physics, focused on the study of many different topics, among them ab initio wavefunction methods, charge ordering of electrons, heavy fermion behavior and magnetic-order effects. In the institute far reaching fundamental knowledge is available about the influence of high magnetic fields on the states of matter.

Research at the Institute of Applied Physics and Didactic of Physics at the Dresden University of Technology (IAPD) is focused on the field of solid state physics. The research of the IAPD in high magnetic fields is directed on magnetic phase transitions and the study of isotropic or anisotropic magnetic exchange interactions, molecular fields, crystal field effects as well as direct measurements of critical fields of superconducting materials. The institute's experiences with cryo-techniques, measurement procedures and systems have been valuable contributions both to the preparation of the proposal and to the development of the 60 Tesla test installation.

A.IV Users of the Proposed Facility

The applicants expect a great demand of high field experimental time at the new facility. This is confirmed by the fact, that leading high field facilities, e.g. in Tallahassee and Grenoble, presently get more proposals than could be satisfied, and that the number of their users has been substantially increased over recent years.

IV.1 Services

The HLD is planned to be a multi-user facility open to a wide range of users from European and non-European countries. With regard to the complexity of the techniques and the level of expertise needed, users will be supported by qualified local scientific and technical staff members. More than half of the human resources planned for the HLD will be occupied with user support.

The allocation of magnet time and the setting of priorities for different experiments is planned to be done by an independent international program committee. The use of

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[4] Wissenschaftsrat: Stellungnahme zum Institut für Festkörper- und Werkstofforschung Dresden e.V. (IFW). 2000, p. 197.

the facility will be free of charge for universities and research institutes. Cost covering fees would only have to be paid for industrial use.

In a first step, three user stations are envisaged which will be extended to six in the coming years. The duration of experiments performed by a single user may vary between a few hours and a couple of weeks.

Different needs of diverse user groups will be reconciled by
- providing three types of magnets with different maximum fields, pulse times and bore diameters;
- providing a wide range of universal measurement methods and equipment adaptable to specific needs of various users;
- designing the sample environment to be prepared for special user needs
- providing high-brilliant infrared radiation from FEL.

Also, high-performance equipment for measurement value logging and electronic data processing will be available to external users as well as the general infrastucture of the FZR (He-liquifier, library, machine shops, computing center etc.).

IV.2 Scientific Education

The HLD will focus on an integrated research and education effort by establishing and fostering collaborations with universities. This effort is ensured by the fact that the Dresden University of Technology will participate in the implementation and operation of the facility and the fact that all directors of the proposing institutes are professors at this university. The collaboration with other universities is also well established. PhD-students and post-docs will be working in the laboratory, both on research topics and on high field technology, material characterization and development. These activities are expected to be a sound education background for future scientists, engineers and technical staff.

Future scientists trained at the HLD would be best prepared for a scientific carrier in solid state physics and material science as well as for research and development work in the whole range of branches where magnetism and magnetic fields as well as pulsed high-current and magnetic field technologies are used.

IV.3 Public Relations

The project was presented at various scientific conferences and the presentation to the general public has begun, at least on a regional scale. These efforts are planned to be continued and extended. Regular training days for high school teachers, guided excursions for school classes as well as a "Tag der offenen Tür" once a year are envisaged.

A.V Project Management, Location, Costs and Schedule

V.1 Project Management

All five institutes involved in the proposal will participate in the realization of the project. They have charged the FZR with the responsibility for project planning and management because the HLD is planned to be established on the FZR site. Essential decisions concerning the operation, use and further development of the laboratory remain in the responsibility of the involved institutes which will establish a Board of Directors. How to involve Associated Members (e.g. Charles University Prague, Institutes of the Czech and Polish Academy of Science, Technical University Vienna) will be decided later.

The HLD will be headed by a director who will be under control of the Scientific Director of the FZR and simultaneously should held a professorship at the Dresden University of Technology. Further, the responsibility will be structured into two subdivisions, one of them being concerned with the operation, maintenance, and further development of the facility, and the other one caring about user service, in-house research program, and experimental techniques.

An external advisory board consisting of leading representatives of the international high field community will also be established.

V.2 Location

The proposed HLD is planned to be built on the FZR site, closed to the radiation source ELBE where an FEL for the middle to far infrared is currently under construction. The posture of the new building planned for the high field laboratory will allow to lead the infrared radiation of the free-electron-lasers directly into the high field facility. The building will mainly comprise rooms for power supply systems, machine workshops, office rooms as well as 6 double laboratories each equipped with a high field magnet and with the appending shielded experimental facilities. Further offices and laboratories especially for external users are available in adjacent buildings of the FZR. Some of the technical equipment of the ELBE radiation source can be shared with the high field laboratory, e.g. for the supply of cryo-liquids.

Advantageous locational factors of Dresden/Rossendorf are:

- large and competent user community in and around Dresden connected within a functioning co-operative network;
- the world-wide unique combination of a pulsed high field laboratory up to 100 Tesla with high quality radiation of an FEL for the middle and far infrared radiation;
- high quality and capability of existing infrastructure at the FZR;
- experience in materials development necessary for a 100 Tesla facility;
- possibilities for up-scaling and enlargement if necessary;
- bridging position of Dresden (locational and through existing co-operations) to user groups in middle and eastern Europe, especially to those acceding the EU in the near future;
- attractiveness of Dresden as a growing high-tech location.

V.3 Costs

Investment and operating costs have been assessed on the basis of experience values which have been confirmed during the development, implementation and operation of the pilot 60 Tesla facility. For larger investments (e.g. power supply components, measuring systems, building) the applicants obtained quotations of various suppliers.

V.3.1 Cost Estimates for Development

Components	**Total Staff (FTE[5])**	**Capital Cost (million €)**	**Staff Cost (million €)**	**Total Cost incl. Staff (million €)**
R&D	21	1,177	1,050	2,227

V.3.2 Cost Estimates for Construction

Components	**Total Staff (FTE)**	**Capital Cost (million €)**	**Staff Cost (million €)**	**Total Cost incl. Staff (million €)**
Materials, Test Coil		0,70		0,70
High Field Coils		2,80		2,80
Power Supply		9,30		9,30
Safety, Control etc.		1,00		1,00
Experiments		4,20		4,20
Building		5,10		5,10
Personal	28/4 years		1,40	1,40
Construction Total		23,10	1,40	24,50

Development and Construction Total	24,28	2,45	26,73

V.3.3 Cost Estimates for Operation/per year

Operation	**Capital Cost (kilo €)**	**Staff Cost (kilo €)**	**Total Cost incl. Staff (kilo €)**
Staff		1.600	1.600
Operating Cost	1.300		1.300
Regular Replacement or Refurbishing	800		800
Maintenance			
Operation Total/a	2.100	1.600	3.700

[5] FTE = full time equivalent one man per year.

V.4 Schedule

A detailed Technical Design Report (TDR) was completed in 1999.

Date	Planning/Construction
2002	- Experimental and development work at the 60 Tesla pilot facility - Materials development - Planning of building, of power supply, of laboratory lay-out
2003	- Construction of building - Components of power supply - Materials development - Equipment for coil winding; test coils
2004	- Completion of building - Power supply - Technical equipment for laboratories and workshop - Safety; controlling; data acquisition - Production of final material for coils; coil winding and tests - Cryo and vacuum equipment
2005	- Completion power supply; connection to laboratories - High-field coils: completion and tests - Experimental equipment; data acquisition; cryo and vacuum - Connection of laboratory to FEL of ELBE radiation source - First test runs
2006	- Completion of high-field coils - Completion of experimental equipment - Opening of the laboratory for experiments

B. Statement and Recommendations

B.I Field of Research

Due to its fundamental importance in nature and its significant influence on the state of matter, high magnetic fields are of great interest in a wide variety of scientific disciplines such as semiconductor physics, the broad field of magnetism and metals, strongly correlated electron systems, chemistry, spin chemistry, complex fluids, life sciences, biology, medicine, magnetic resonance and optical spectroscopy.

There is a world-wide consensus that much higher magnetic fields than presently accessible will be needed in the near future to foster new scientific challenges. For instance, semiconductor physicists see a clear need for magnetic fields of more than 50 Tesla to explore the new physics associated with new materials and structures processed on the nanometer scale. The availability of these high fields will open up new possibilities in fundamental research on quantum liquids in semiconductors and will also be of great assistance in the characterization, further development and exploitation of novel semiconductor materials.

Going to 100 Tesla long pulsed magnetic fields picks up on this challenge and is a major technological and scientific step forward which will enable substantial progress in condensed matter physics and material sciences. The sub-panel expects that the following important questions can be tackled with the proposed facility:

- Magnetism of metals (e.g. high field metamagnetic effects, magnetoresistance, magneto-elastic effects);
- Magnetism of superconductors (e.g. Fulde-Ferrel-Larkin-Ovshinikov (FISC) phase);
- Magnetism of strongly correlated systems (e.g. heavy fermions, Kondo insulators, spin fluctuators);
- Nanotubes and nanostructures in high magnetic fields (e.g. carbon tubes);
- Semiconductors (e.g. Quantum Hall Effect; metal-insulator transition, narrow and wide gap semiconductor spectroscopy, Wigner crystal);

- Materials science aspects (e.g. magneto-resistance, colossal magneto-resistance, high-coercive materials).

German research in high magnetic fields, mainly using the High Magnetic Field Laboratory at Grenoble, has been particularly productive and successful in the last decades. The planned facility would be a singular opportunity to establish a world-wide leading laboratory for pulsed high magnetic fields, and thereby strengthen research with high magnetic fields in Germany. Also, it opens the prospects for developing Forschungszentrum Rossendorf (FZR) into the central European laboratory in this field of research.

B.II Scientific Program

The presented scientific program is extremely strong and well defined. It results from a highly productive interaction between experimentalists, engineers and theorists coming from different strong institutions located at Dresden. The wide range of addressed research areas documents an excellent potential not only for developing but also successfully using a 100 Tesla high magnetic field facility.

Long pulsed (10 to 20 ms, i.e. quasi stationary) magnetic fields of up to 100 Tesla will certainly enable novel and innovative research techniques that are especially important for condensed matter physics and material sciences. The combination of a pulsed high magnetic field laboratory up to 100 Tesla with high quality middle- and far-infrared coherent radiation produced by the ELBE Free Electron Laser (FEL) will open up additional unique research perspectives. The proposed facility will provide the opportunity to combine materials science (metals, composites and high tensile strength materials) with further developments of magnet technology. For these reasons, the sub-panel is convinced that the envisaged scientific program as well as the technical characteristics of the proposed facility will be unique in Europe. The scientific benefit in relation to the investment cost is judged to be very high.

B.III Technology

The proposed magnet technology is ambitious but realistic, due to the fact that it will employ state-of-the-art materials, engineering and designs. Technological innovations can be, however, expected from developments of conductor materials for the high field coils by the Institute for Solid State and Materials Research Dresden (IFW). There are alternative technologies for the power supply that is being proposed. However, the sub-panel is convinced that the proposed very large capacitor bank is the appropriate solution for the planned facility.

The modular power supply developed by FZR represents a next generation capacitor bank power supply. It is a flexible design that will very likely perform as predicted, because the proof of principle has been already achieved at the pilot facility.

The proposed approach of advancing step-by-step to a 100 Tesla magnet is the correct way to go about it because each intermediate step already opens up new capabilities for science, and allows developing the technology adiabatically. The prospects of reaching the goal of 100 Tesla is judged to be high.

B.IV Project Management, Location, Costs, Schedule

The written proposal is solid, also with regard to project management. The sub-panel very much appreciates the well established collaborations of the wider Dresden scientific community. Also, the growing international collaborations that range from East European institutions in Prag, Warschau, Breslau and Moskau to West European and American laboratories are highly recognized. Especially the further development of international collaborations on magnet design and safety technology is well underway.

There are distinct advantages to the proposed location at FZR. Within the Laboratory it allows the magnets to be located close to the ELBE FEL. Also, FZR is part of Dresden's high concentration of very strong materials science and condensed matter research institutes. The FZR has substantial experience in planning and building medium-scale facilities such as the radiation source ELBE including the FEL, while the IFW, hosting the 60 Tesla test facility, has seminal experiences in design and construction as well as operation of a high field facility. Altogether, the five involved institutions have profound technical and scientific expertise in the relevant fields. Their recent results in materials research on ultra-strong conductors, in the development of suitable power supply systems and measurement facilities prove their high potential to realize the first long-pulse 100 Tesla facility in Europe. However, additional engineering expertise will be needed. The sub-panel therefore appreciates FZR's current efforts to bring an expert for magnet technology into the laboratory. Also, in order to protect the magnets and the users, the sub-panel recommends to undertake formal safety reviews of the magnet designs as well as of the operating procedures.

In Europe, similar facilities are currently planned in Toulouse and are under consideration in Nijmegen. However, the demand for magnet time in Europe is large enough and the investment costs are relatively moderate to justify more than one laboratory for pulsed high magnetic fields in Europe. Also, the combination of an infrared FEL with high magnetic fields at FZR will be a world-wide unique option.

The estimated budget for the project is very tight since it was developed in 1999 and has not been increased since, even for inflation. Experience at other international magnet laboratories suggests that the proposed big magnets may be more expensive than currently assessed. The additional cost of an in-house team of professional engineers should also be taken into account.

The proposed facility will not require international but only national funding. The sub-panel received assurances of the State of Saxony's strong support of the project.

The schedule is judged to be realistic. It is based on the experiences gained at the 60 Tesla test facility.

B.V Users of the Facility

The facility will not only be used by Dresden scientists but also by research groups from other German institutions. Furthermore, the sub-panel is convinced that

European and international user groups will also be attracted by this unique facility. The strongest interest for the facility will be in the whole range of condensed matter physics; for example, in the physics of semiconductors, magnetism, superconductivity as well as of atoms and molecules.

The European community of researchers that would be interested in such a facility numbers around 500. It is estimated that the facility will be able to accommodate about 100 users, 10-15% of them conducting research in combination with the FEL.

The sub-panel strongly supports FZR's efforts to set up a user program and to establish an independent international program committee that evaluates FZR's in-house research program along with external proposals. However, in order to support and advance the existing scientific potential in the Dresden area, the strong demand of experimental time that is expected from local research groups should be given preferential priority.

FZR's intention to focus on an integrated research and education effort by establishing and fostering collaborations with universities is fully supported. Due to the involvement of the TU Dresden in the construction and future operation of the laboratory, excellent opportunities for education of a future generation of scientists at a first-class research facility can be expected. Training of students and young scientists should also be supported by special seminars and workshops.

B.VI Transfer of Research Results

Research in high magnetic fields and technical development of high field facilities generally have a strong impact on industrial products and technologies. It is therefore highly appreciated by the sub-panel that the Dresden scientific community is already explicitly addressing technological innovations and striving towards appropriate transfer mechanisms for industrial applications.

A high impact of future research results is guaranteed due to the international reputation of the Dresden research groups. Referring to the recent top results of the IFW Dresden, the sub-panel expects further significant progress in the development of new materials for magnet technology. The development of new and/or stronger magnetic materials will have a strong impact on all areas of electrical engineering products. In general, the enlargement of the magnetic field range up to 100 Tesla will be essential for the development and application of semiconductors, superconductors and magnetic materials.

C. Conclusion

Going to 100 Tesla long pulsed magnetic fields is a major technological and scientific step forward. In a unique constellation, the magnets also permit experiments with the very intense infrared beams of the Free Electron Laser ELBE that is now beginning to operate at the Forschungszentrum Rossendorf (FZR). The proposed facility would open up new opportunities in a wide area of science, mostly in magnetism of materials and nanostructures, but also in chemistry and biotechnology.

While the magnets and their power supplies are technically ambitious, the required technical know-how is available within the proposing consortium of research institutes at Dresden, and major components have already been demonstrated. The proposal for this facility has been carefully worked out over several years. Although the costs have last been evaluated in 1999 the proposal is well developed and complete.

The scientific and technical support is solidly embedded in an impressive array of excellent scientific and technical institutes in the Dresden area. Altogether, the five involved institutions have profound technical and scientific expertise in the relevant fields. Their recent results in materials research on ultra-strong conductors, in the development of suitable power supply systems and measurement facilities prove their high potential to realize the first long-pulse 100 Tesla facility in Europe.

While the regional user community will be very strong and could probably saturate the time available for experiments, this facility would be attractive to an international research community. It would be a singular opportunity to establish a world-wide leading laboratory for pulsed high magnetic fields. Thus, it opens the prospect for developing FZR into the central European laboratory in this field of research.