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RESEARCH AT HIGH MAGNETIC FIELDS IN EUROPE, THE NEW FACILITY IN DRESDEN

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Introduction

In nature, the magnetic field acts as a fundamental thermodynamic property like temperature or pressure. For this, the magnetic field plays a decisive role in many facets of nature, and in consequence, is of importance in several natural sciences. In particular, the understanding of magnetic properties of matter and the interplay of magnetism with other quantities is a challenging field of research. Under extreme conditions, like low temperatures, high pressures, and high magnetic fields, new interesting properties of matter can appear and the understanding of materials properties can crucially be gained.

Further, the manifold magnetic effects in nature and in particular the magnetic properties of matter are a rich source for technological innovations. Historically, there is an immense number of inventions like the compass, electro motor, generator, relay, magnetic brake, levitating train, nuclear magnetic resonance tomograph, hard disk drive, magneto-electric random access memory. Nowadays, in transport, energy production, medicine, communication, data storage, and other areas of daily live, magnetic systems, components, and properties are used in a large variety.

In the last decades, the application of high magnetic fields became a powerful research tool. Especially in solid state physics important discoveries like the integer quantum Hall and fractional quantum Hall effect, both honoured with the Physics Nobel Prize, are based on experiments in very high magnetic fields.

In order to establish a large modern user facility with unique experimental possibilities for science in high magnetic fields and in order to provide an easy access for the high field community in Europe, the Dresden High Field Project has been created. Since 2003 this facility is under construction. In this paper, we give a snapshot on the status and some recent achievements in the course of the project. The Dresden High Field Laboratory for nondestructive pulsed magnetic fields up to 100 T will open its doors as a user facility in January 2007.

A) Research at High Magnetic Fields in Europe

In Europe, the research in high magnetic fields has a long tradition. Over decades, a list of institutes has been established, e.g. in Amsterdam, Berlin, Braunschweig, Bristol, Dublin, Frankfurt, Grenoble, Leuven, Moscow, Nijmegen, Oxford, Parma, Porto, St. Petersburg, Toulouse, Vienna, Wroclav, and Zaragoza [1]. Some of them have or have had a worldwide top ranking. However, the leading role of Europes institutes has (at least partly) been lost through the large investments as well as technical and scientific achievement in the modern high magnetic field user facilities in the United States (Tallahassee and Los Alamos) and Japan (Tsukuba, Kashiwa, and others) [1].

The present record values for static magnetic fields, 33 T for resistive coils and 46 T for a hybrid coil have been established in National High Magnetic Field Laboratory (NHMFL) of the United States in Tallahassee [2]. However, these values are limited by the properties of the materials used for the coils, the cooling power necessary to keep the coils intact, and the energy stored in the necessary power supply. Reasonable expectations predict that static fields will be limited to values of about 50 T for the foreseeable future [2]. Comparing the capital and running costs for existing static field facilities and pulsed field facilities, it is obvious that the cost for a 100 T, 10 ms pulsed facility is substantially less than the cost for a 40 T static facility. In addition, pulse lengths in the range of 10 to 100 ms are quasi–static which means that most of the experiments can be performed this way, excluding possibly only neutron scattering. As a summary, it is fair to state that with pulsed, non destructive high field technology one can go to higher field values with less money and still can perform a large number of experiments related to high field science. Because of that reasons, the NHMFL also aims at a record for nondestructive pulsed magnetic fields. The NHMFL started a project in order to build up a 100 T pulsed field coil system at the Los Alamos research center.

In Europe, there is a strong desire for a 100 T facility, too. In a study report of November 1998 "*The Scientific Case for a European Laboratory for 100-T-Science*" [3], the European Science Foundation states: "*The science community in Europe actively engaged in experimental research based on highest magnetic fields comprises about 500 researchers.*" This means that there is a large community of scientists in Europe interested in the use of the highest possible magnetic fields for their research. "*The most urgent need for European action is for 100 T long pulsed fields …. The likely capital and running costs … are of the order of 50 MEuro and 5 MEuro p. a., respectively.*"

Due to the strong local scientific community in Dresden with a high contration in solid state physics and the experience in building up large scale facilities, a consortium of five institutes located in Dresden has jointly created a proposal for the building of a 100 T user facility. The consortium consists of the Forschungszentrum Rossendorf, FZR (represented by F. Pobell, M. Helm), the Leibniz-Institut für Festkörper- und Werkstoffforschung, IFW (H. Eschrig, L. Schultz), the Max-Planck-Institut für chemische Physik fester Stoffe, MPI-CPFS (F. Steglich), the Max-Planck-Institut für Physik komplexer Systeme, MPI-PKS (P. Fulde), and the Institut für Angewandte Physik of the Technische Universität Dresden, TU-DD (M.

Loewenhaupt, J. Wosnitza). This proposal (available in Ref. [4]) has been reviewed by the German Science Council (Deutscher Wissenschaftsrat) in its evaluation of nine large scale science projects in Germany. The Science Council has grouped the proposal for nine projects into three groups. The first group contains two proposals, one of which is the Dresden High Field Project. The statement relevant for our project is: "*The first group which contains large facilities, the realization of which implies research infrastructures of a new quality and places expectations into fundamental development of the related research area and into new scientific inside, is recommended without reservation by the Wissenschaftsrat to be founded.*" As a consequence, the federal science ministry of Germany and the science ministry of Saxony have agreed to support the project with an expenditure of about 25 MEuro (about half the budget estimated in Ref. [3]) distributed over the years 2003 to 2006.

B) The new High Magnetic Field Laboratory in Dresden, HLD

The new laboratory will be distinguished by its high magnetic field values of up to 100 Tesla with pulse durations of typically 10 ms. and its proximity to an infrared-free-electron-laser-facility [5] at the Forschungszentrum Rossendorf. This combination will enable users to perform unique high field infrared spectroscopy experiments. In addition, recently the feasibility of nuclear magnetic resonance experiments in pulsed magnetic fields has been demonstrated at the IFW, Dresden.

1) Time Schedule

In 1998 the proposal of the project has been jointly submitted for funding by the FZR, IFW, MPI-CPFS, MPI-PKS, and TU-DD. In a pilot project a 1 MJ / 10 kV capacitive pulsed power supply has been developed at the FZR and installed in the IFW in 1999. Since that time the pilot lab at the IFW, further equipped with several pulsed magnets, bought from the high field labs in Tallahassee and Leuven, is in intensely use. In 2000, several experimental methods have been established there. In 2001 we have already started with the planning of the Laboratory building, its technical infrastructure as well as its safety installations. During 2002, the plans for the building have been fixed. The planning of a new 1.44 MJ, 24 kV capacitve pulsed power supply has been started. In 2002, further, the evaluation and recommendation of the German Science Council, as well as the approval of funding of the ministries happened. We have immediately started with the realisation of the lab building and the planning of 50 MJ pulsed power supply, later with the machine shop building and its technical equipment for coil production. In 2004 we have already completed both buildings and the 1.44 MJ / 24 kV module. Further we have successfully started our own production of pulsed field coils.

As next steps, the installation of first parts of the 50 MJ / 24 kV pulsed power supply and a long list of pulsed magnetic field coils will follow in 2004. In 2005 the 50 MJ/24 kV pulsed power supply will be completed and field coils for the higher energy range are planned. In 2006 the experimental instrumentation, in particular the infrared-beam line between the magnet lab and the neighbouring radiation source ELBE will be installed. In addition user field coils will be produced. In January 2007 the opening of Dresden High Magnetic Field Laboratory as a user facility is scheduled.

2) Scientific Objectives

With magnetic fields up to 100 T, a wide field of research can be covered. The materials which can be considered as sample candidates vary between elemental solids and complex molecules. Besides the not assessable number of stable samples, also samples under chemical nonequilibrium conditions, i.e. the study of the influence of high magnetic fields on chemical reactions, could be of interest.

In this paper, we restrict ourselves to mention some prominent examples of possible experiments in high magnetic fields:

- critical fields of high temperature superconductors
- study and characterisation of metals and semiconductors
- organic conductors in high magnetic fields
- low dimensional spin systems in high magnetic fields
- the search for magnetic field induced superconductors
- phase diagrams of magnetic materials, e.g. antiferro-, ferri-, and metamagnets
- nuclear magnetic properties in high magnetic fields
- low dimensional semiconducting structures in high magnetic fields
- strongly correlated electron systems in high magnetic fields
- influence of high magnetic fields on molecular systems und clusters
- influence of high magnetic fields on complex fluids

For more details, we like to refer to Vol. 2 of Ref. [1], on our recent publication [6], as well as on our homepage [4].

3) Facility Buildings

In the project, there are two new buildings which have been built in 2003 and 2004. Fig. 1 shows the layout of the new high magnetic field laboratory building.

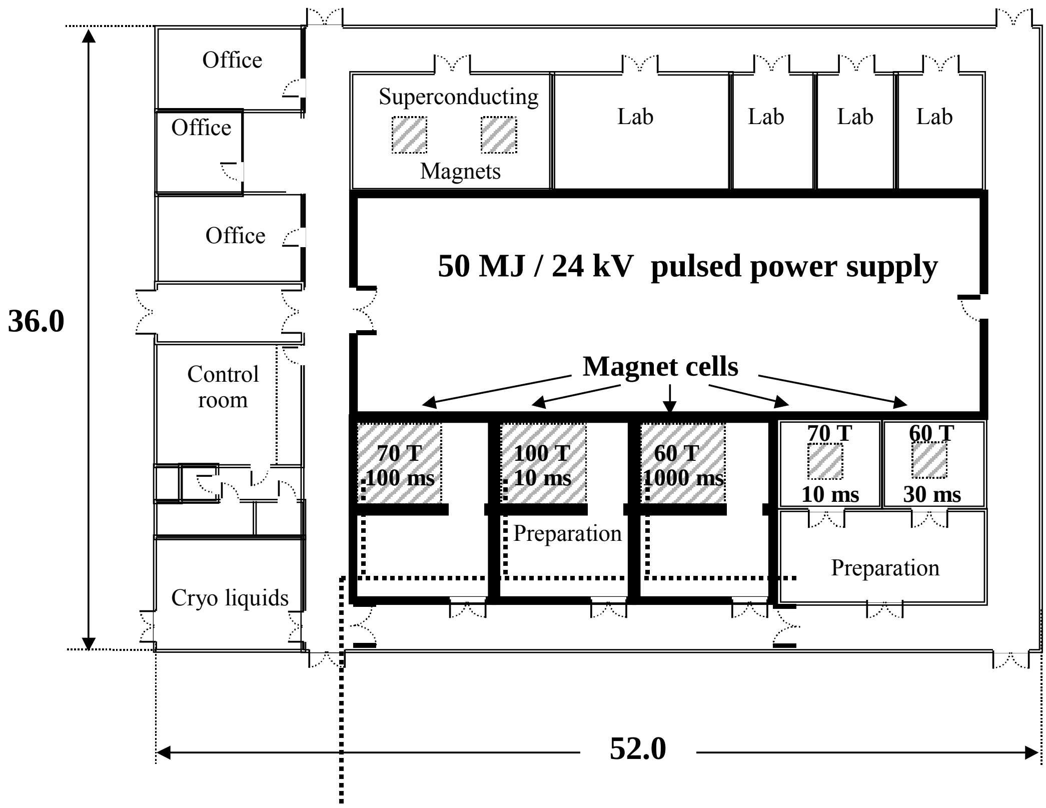

Fig.1 *Ground plan of the Dresden High Magnetic Field Laboratory. The pulsed magnets are located in pits (hatched areas). The key parameters (maximum field, pulse time) of these magnets are printed at the location of their cells. The bold dotted lines are a rough sketch of the infrared light pipes which run through a tunnel below the main floor and are coming from the free-electron laser facility.*

The laboratory building has a large central hall in which the 50 MJ / 24 kV pulsed power supply for the pulsed field coils will be installed. On one side, there are five laboratories for the pulsed field coils. The three main magnets, whose parameters (maximum magnetic field and pulse length) are given in Fig. 1, will be placed in pits of dimensions 2.9 m x 4.0 m x 4.0 m. They are protected by specially arranged concrete walls reinforced by non-magnetic stainless steel. Outside of the safety cabins for the five magnets there will be the equipment for the experiments. The whole set-up (capacitor bank control and data processing of the experiments) will be operated via glassfibre optics from a control room using Ethernet standard. On the other side of the hall, opposite to the power supply, there are a laboratory for large superconducting magnets as well as four additional laboratories for sample and experimental preparation. The laboratory building will be at a distance of about 20 m from the free-electron-laser-facility [5] and will be connected to it by a tunnel through which the infrared light pipe (dashed line in Fig.1) of a total length of about 60 m (main pipe + each 15 m for the connection between a pulsed magnet and the main pipe including vertical lines) will run.

The foundation stone of the laboratory building has been layed at the end of May 2003. In September 2004 (see Fig. 2), it has been finished including several technical installations, e.g. a central prevacuum system, helium recovery system, central liquid nitrogen transfer line to the magnets, as well as several safety installations like a interlock and a transponder system, photo electric guards, as well as video cameras.

Fig.2 *Dresden High Magnetic Field Laboratory (picture taken in September 2004) in front of the building of the radiation source ELBE and its far infrared (FIR)-free electron lasers at the Forschungszentrum Rossendorf [5].*

The second building wich contains the machine shop for the production of the pulsed magnetic field coils as well their test facility has been built between November 2003 and March 2004. Fig. 3 (picture taken in September 2004) shows the interior of the machine shop. In detail, the machine shop is equipped with a special coil winding machine for coils of the maximum dimensions length = 1,20 m, diameter = 1,0 m, weight = 3000 kg, a workshop press for loads up to 200 tons for the application of prestresses to the coils, a drying ofen for the curing of stycast compounds, various machine tools, etc. For the tests of the coils, the machine shop hall also contains a 1.44 MJ / 24 kV / 40 kA capacitive power supply, a test pit and a safety test box (safety installations to prevent damages in the possible case of coil burst), electronic test equipment, as well as a control room.

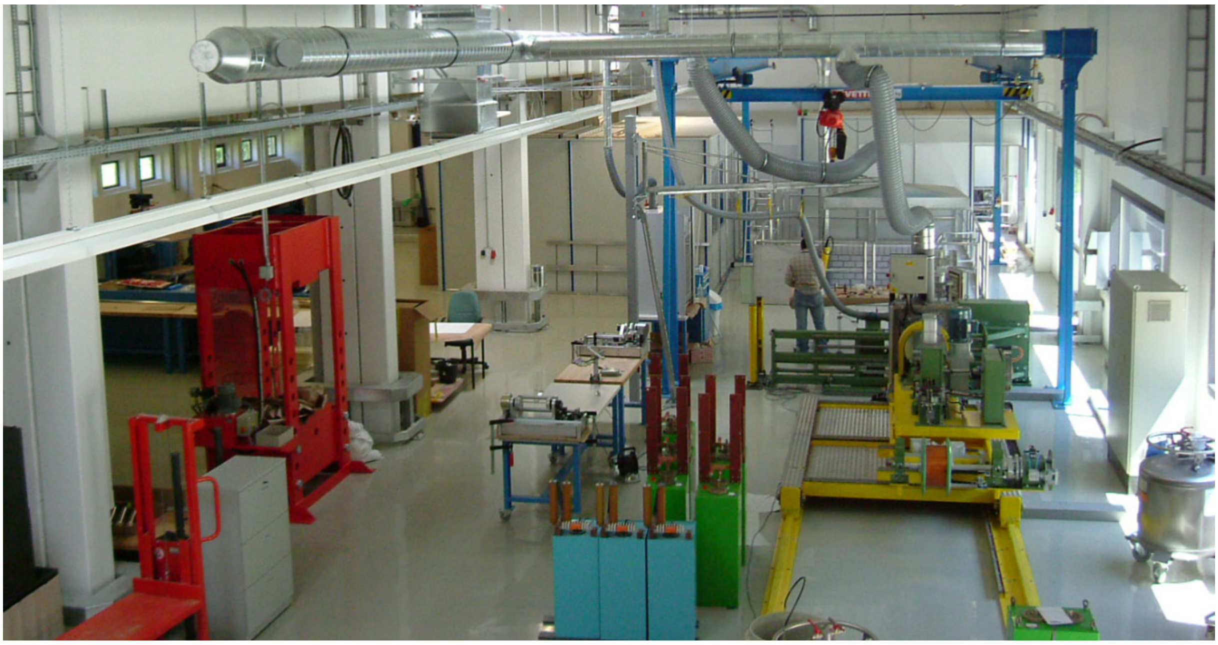

Fig.3 M*achine shop (picture taken in September 2004) for the production of the pulsed magnetic field coils of the Dresden High Magnetic Field Laboratory.*

4) Pulsed Power Supply

In the beginning of the project, a capacitor bank consisting of four independent 250 kJ modules, at a maximum charging voltage of the capacitors of up to 10 kV and with a short cut current of 90 kA has been set-up for test purposes [4, 6, 7]. It contains 12 capacitors (C = 1.667 mF each) of high energy density type (0.75 MJ/m^3) made of metalised polypropylene foils. These capacitors have so called self-healing properties and a long lifetime, but they cannot be charged with reversed voltage. Therefore, a novel circuit has been designed that allows reversed voltage while maintaining the inner part of the coil at ground potential, and the thyristor switch in the hot branch of the circuit (for details see [6, 7]). An optional combination of 1 to 4 modules in parallel can be discharged to a high field coil via thyristor switches. This capacitor bank is under operation as a pulsed power supply for the pulsed magnetic field coils of the pilot laboratory since 1999 [4].

As a next step towards the design of the 50 MJ capacitor bank and the relevant technology, a 1.44 MJ / 24 kV module has been built during 2002 to 2004. The module consists of 16 capacitors with each about 310 μF / 24 kV (90 kJ) with a life time of more than 30.000 shots in accordance with normal operation (30 % voltage reversal). The short cut current will be limited to about 40 kA via a safety coil with an inductance of 2 mH. The charge time using two power supplies for positive and negative fields with 16 kJ/s each will be 90 s. The thyristor switch is composed of 5 light triggered thyristors with integrated overvoltage protection connected in series with a repetitive peak reverse voltage of 8 kV each. The crowbar circuit with which the magnetic field pulse shape can be modified consists of three selectable high energy disc resistors with R = 0.6 Ω, 1.2 Ω, or 2.4 Ω, respectively. The bank can be discharged with a resistor of 100 Ω via a normally (no electric control power) closed high voltage relay in about 2 s. Different methods of diagnostics, e.g. the measurement and analysis of inductance, resistance, current and voltage waveforms as well as the current derivative in order to test the condition of the capacitors and the high magnetic field coil are included in the module.

Fig.4 P*icture of the 1.44 MJ / 24 kV / 40 kA module which is used in the test facility of pulsed magnetic field coils of the Dresden High Magnetic Field Laboratory.*

As a next step, we decided to optimize the 1.44 MJ / 24 kV / 40 kA module for the use in the large 50 MJ / 24 kV power supply under industrial aspects. For this we have engaged an industrial vendor, the Rheinmetall group, to cowork in the planning, to test components, to produce, to install, and to start up the whole 50 MJ/24 kV facility.

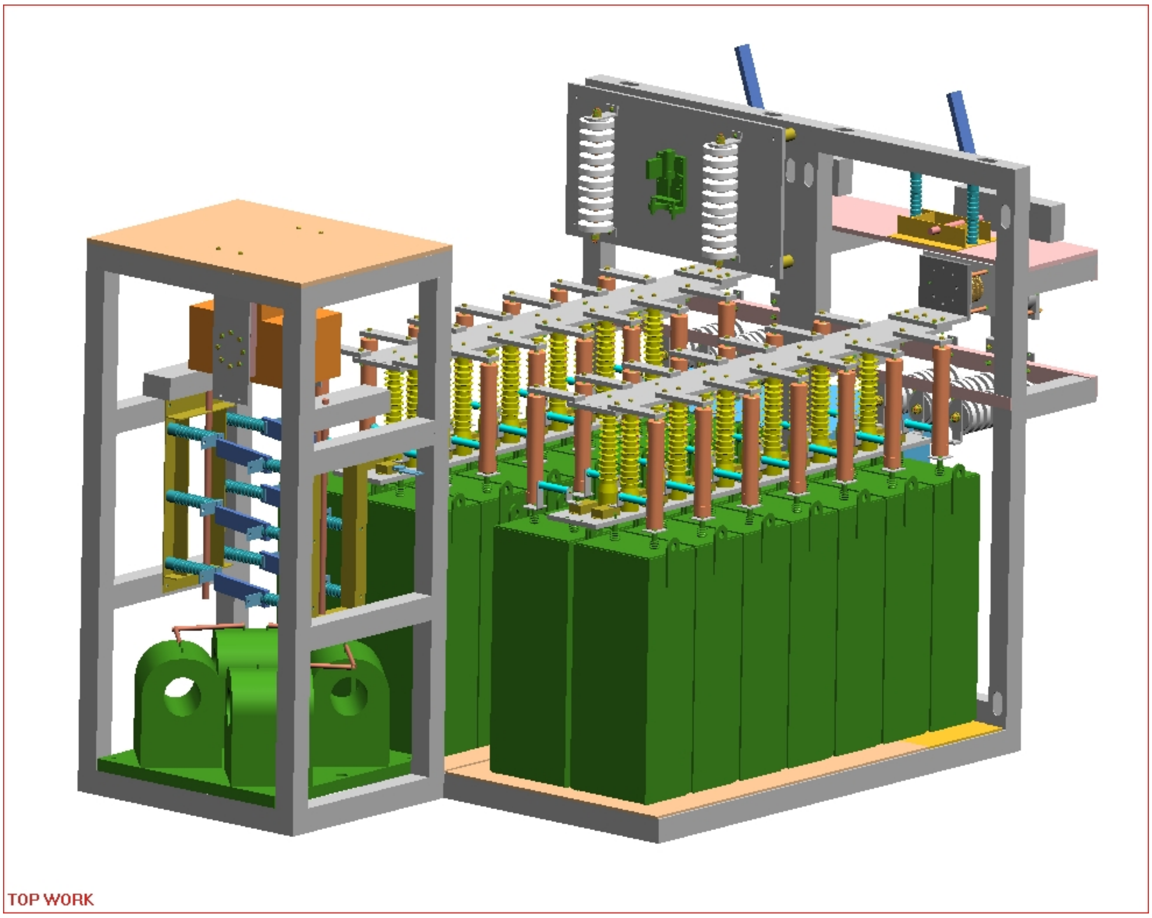

Fig.5 *Drawing of one of the 2.88 MJ / 24 kV / 25 kA module which will be installed in the 50 MJ / 24 kV capacitive pulsed power supply of the Dresden High Magnetic Field Laboratory.*

Further we have decided to split up the capacitor bank in 15 modules with an maximum energy content of each 2.88 MJ (24 kV, 25 kA, see Fig. 5; module No. 1 – 11 and 16 – 19, see Fig. 6), 4 modules with each 1.44 MJ (24 kV, 37 kA, No. 12, 13, 14, 21, see Fig. 6), as well as 2 modules with each 0.5 MJ (24 kV, 100 kA, No. 15 and 20, see Fig. 6). The first 1.44 MJ / 24 kV module will be installed in the capacitor hall of our laboratory building in October 2004. All modules are equipped with switches in order to connect (disconnect) them to (from) current collectors in the following way: No. 1 – 11 can be connected to collector 1, No. 16 – 19 alternatively to collector 1 or 2, No. 12 – 14 to collector 3, and finally modules 20 and 21 directly to coils located in the two pulsed field chambers designed for energies up to 2 MJ (see Fig. 6). The collectors 1 and 3 as well as module 15 can be switched to the three magnet chambers designed for energies up to 50 MJ (see Fig. 6). Collector 2 is exclusively connected to the middle of the 50 MJ pulsed chambers. Under this modular concept, we are able to energize coaxial multi coil systems with up to four separate subcoils. This separation improves the possibilities in order to achieve maximum fields up to about 100 T, not produced up to now on a ms time scale. In addition, this flexible modular concept allows a large variety of coil designs important for the various experimental methods described in paragraph 6.

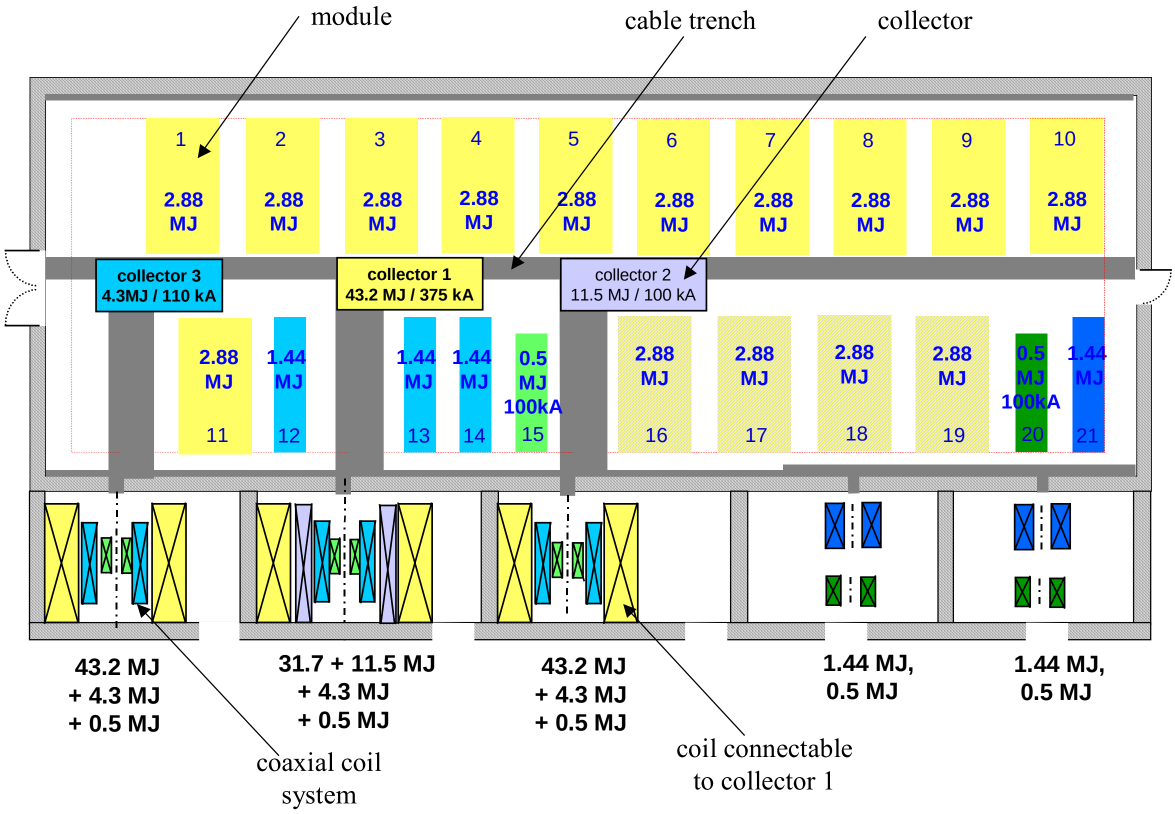

Fig.6 Sketch of the modular *50 MJ / 24 kV capacitive pulsed power supply for the pulsed field coils of the Dresden High Magnetic Field Laboratory (for details, see text).*

The whole 50 MJ pulsed power supply is controlled via an industrial integrated automation system based on glass fiber communication between capacitor hall and a separate control room. For fast communication, e.g. for monitoring the pulsed currents measured on each module and each collector, but also for the transmissiom of video pictures from the capacitor hall to the control room, the facility will also be provided with fast Ethernet.

5) Pulsed Magnetic Field Coils

Since the last decade, there has been an essential progress in the design of magnet coils as well as in the development of new strong conductors and new reinforcement materials, e.g. synthetic fibers as PBO ("Zylon"), used for coils [1]. A variety of magnet specifications, e.g. maximum field, pulse duration, inner bore diameter, mechanical properties of wires, reinforcement materials, conductivity of the wire, as well as many others essentially affect the coil design. Pulsed magnets for a relatively short pulse duration (less than 100 ms) and magnetic fields up to approximately 70 T are usually designed as a single compact coil. Longer pulses and higher fields result in large coaxial dual or multi-coil systems with several sections. An important part of the magnet design are extensive computer simulations on different aspects of the magnet behavior. Computer simulations are usually based on analytical approximations and numerical methods like finite element analysis (see also Fig. 6). Some preliminary computer simulations of the projected magnets are described in Ref. [6].

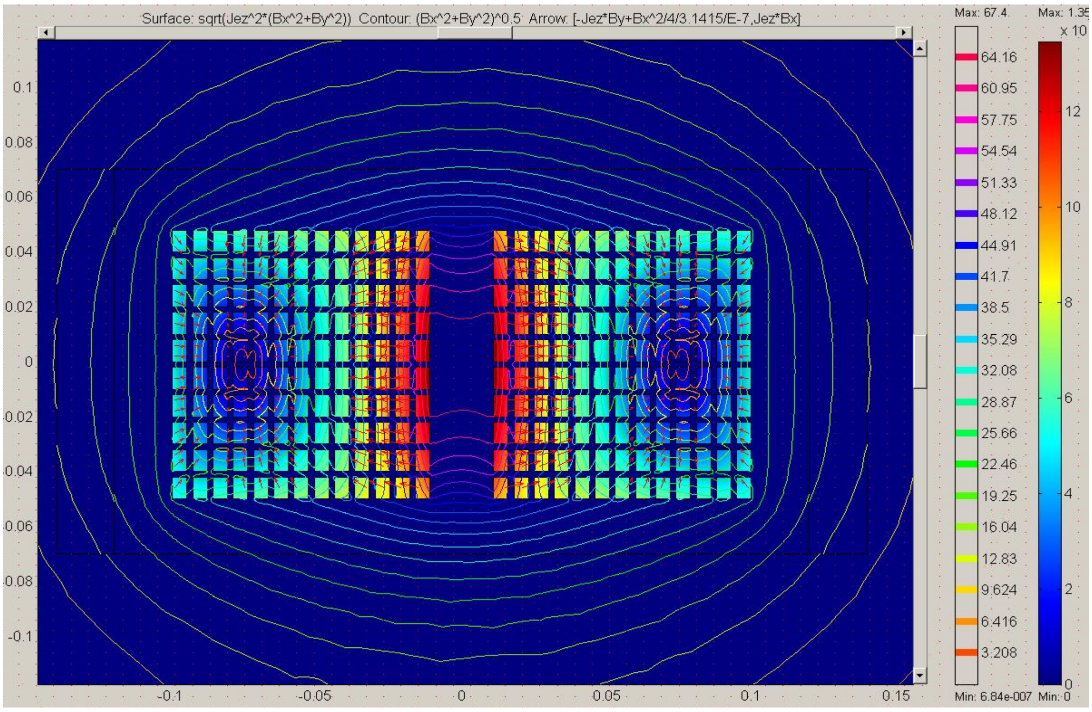

Fig. 6 *Finite element analysis of a cylindrical field coil with the commercial software package FEMlab. The colored contour lines are equipotential lines of the magnetic field, the surface color on the rectangular wire cross sections (2 times 3 mm) display the Lorentz force density, and the arrows show the direction of the Lorentz forces in the wires.*

The maximum magnetic field B for non-destructive pulsed magnets is mainly determined by the mechanical strength $P = B^2 / 2\mu_0$ of the coil which goes up to about 4 GPa = 40 000 bar for B = 100 T. Stresses of a few GPa are far beyond the ultimate tensile strength (UTS) of good conductors like Al, Cu, Ag and even beyond the UTS of best steels. Only few synthetic fibers as carbon- or PBO-fiber sustain such loads [1]. It is of particular importance to analyse the Lorentz stresses, the plastic deformation and fatigue of the material the coil is made from and, of course, the characteristics of the whole coil. Shear stresses are responsible for the plastic deformation, which can lead to material failure. On the contrary, an isostatic stress does not result in plastic deformation. Thus, it is desirable to have isostatic pressure conditions for the conductor in the coil. One can try to approach the isostatic pressure conditions by optimizing the internal and external reinforcement of the coil.

In order to keep the stresses in the reinforcement layers of pulsed magnetic field coils on a level savely below the ultimate tensile strength, the development of special wires with a high mechanical strength, reasonable electrical conductivity and relatively large mechanical ductility is required. These wires could at least partly contribute to the stability of pulsed field coils. In the Dresden High Field Project, copper based conductors are studied at one of the participating institutes, the IFW Dresden [6].

We have recently started to produce first test coils in our coil production facility. We have been successful in solving technical problems attributed to high voltage insulation, mechanical stability, and cryogenic robustness (the field coils are cooled with liquid nitrogen). In Fig. 7, a magnetic field pulse of one of our first magnets (used energy = 1.0 MJ, U = 24 kV) with a maximum field of 62 T is shown.

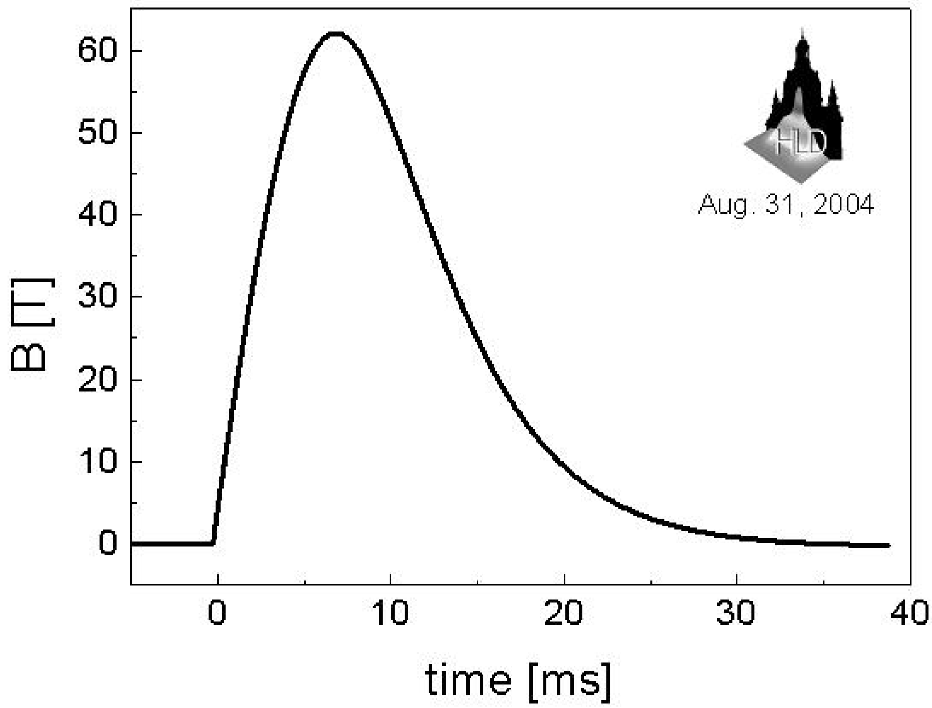

Fig.7 *Magnetic field B versus time with a maximum filed value of 62 T measured in a recent (August 2004) coil test at the Dresden High Magnetic Field Laboratory.*

6) Experimental Techniques

The flexible modular design of the capacitive pulsed power supply (see paragraph 4) of the Dresden High Magnetic Field Laboratory enables a large variety of pulsed field coils in respect of pulse height, pulse duration (ms to s), pulse shape, and homogeneity. For this, a wide spectrum of experimental techniques will be possible which on its part could satisfy the requirements for investigations of quite different scientific objectives in high magnetic fields (see paragraph 2, Vol. 2 of Ref. [1], Ref. [6], as well as our homepage [4]). We will provide equipment for e.g.

- ac susceptibility,
- magnetisation,
- magnetoresistance,
- magnetostriction,
- ultrasound,
- heat capacity,
- thermal conductivity,
- electron spin resonance (ESR),
- nuclear magnetic resonance (NMR),
- cyclotron resonance,
- infrared (IR) and far infrared (FIR) spectroscopy,
- magneto optics

The infrared (IR) and far infrared (FIR) spectroscopy in combination with highest pulsed magnetic fields has been evaluated by the German Science Council to be unique, worldwide. The free electron lasers of the radiation source ELBE [5] will provide wavelengths continously adjustable in the wide range between 5 to 150 µm.

In addition, low temperature cryostats for the K and mK temperature range, superconducting magnets, pressure cells, SQUID magnetometers, and further equipment will be established.

Outlook

The Dresden High Magnetic Field Laboratory located at the Forschungszentrum Rossendorf will open its doors as a user facility in January 2007. World wide unique, the facility will enable infrared spectroscopy at highest pulsed magnetic fields besides a dozen of other experimental techniques. In addition, static fields in superconducting magnets up to 20 T will be available. Besides the wide range for the magnetic field, experiments will also be possible in a wide temperature and pressure range.

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