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Pulsed-magnet design at the Dresden High Magnetic Field Laboratory

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Abstract. The current status of the pulsed-magnet program of the Dresden High Magnetic Field Laboratory (HLD) is reported. The non-destructive pulsed magnets for the HLD include a wide spectrum of coils designed for energies between 1 and 46 MJ, magnetic fields of 60 - 100 T, and pulse durations of 10 - 1000 ms. Various experimental techniques at pulsed magnetic fields will be available for external users soon. Some user magnets for first scientific experiments have been installed and tested. A 8.5 MJ / 70 T mono-coil magnet has been built and first test results for this magnet are presented. The design of a two-coil 46 MJ magnet for magnetic fields above 85 T has been completed. This magnet is under construction now. Important issues of the coil design are numerical simulations of the pulsed-magnet performance. Both analytical approaches and finite-element analysis are used for these simulations at the HLD.

1. Introduction
Within the last decade non-destructive pulsed magnets have become a common tool for high magnetic-field research [1]. These magnets are capable of producing magnetic fields higher than achievable DC fields within a time interval which is long enough for a large number of experimental techniques. Different examples of important opportunities in high magnetic field research are given in Refs. [2, 3]. The Dresden High Magnetic Field Laboratory (HLD) is a new user facility which will provide external users with the possibility of performing diverse experiments in pulsed magnetic field [4]. Various experimental techniques, such as electrical transport, magnetization, ultrasound and magnetic-resonance measurements will be available at the HLD. A particular feature of the laboratory is a nearby free-electron laser facility which will enable high-field infrared spectroscopy in pulsed magnetic fields.

A modular 24 kV capacitive energy supply of 50 MJ has been recently completed at the HLD. In-house planned and constructed magnets include a number of coils designed for energies of 1 - 46 MJ, magnetic fields of 60 - 100 T, and pulse durations of 10 - 1000 ms. In order to fulfill this program the necessary infrastructure accounting for the technical and technological aspects of pulsed-magnet design and fabrication has been established. A new pulsed-magnet core design has been developed at the HLD [5]. In spite of the strong external mechanical support, our magnets are designed in a compact way which is suitable both for a mono-coil and a multi-coil configuration. The core design has been successfully tested for a number of 1 - 1.5 MJ magnets yielding fields between 60 and 65 T and, most recently, for a larger 8.5 MJ / 70 T magnet.
An important issue of the pulsed-magnet design are numerical simulations of the magnets. This can essentially reduce the design time, help to improve magnet performance and to better understand the pulsed-magnet operation. A pulsed magnet can be modeled using an analytical approach. This provides quick estimates for diverse coil parameters like magnetic field, stress, and temperature in the middle plane of the coil. However, in many cases it is necessary to analyze the magnet properties locally at certain positions inside the magnet. The finite element analysis (FEA) is the proper method for such modeling. In our simulations, we use both the analytic approaches and the FEA. These methods supplement each other. There are a number of programs developed especially for the pulsed-magnet design. Here we would like to mention only a few of them: the PULSE and CYCLN software developed at the NHMFL at Tallahassee [6] and the PMDS [7] software from the KU Leuven. We are using commercial FEA programs like ANSYS and COMSOL for the finite element analysis. Some modeling results are shown in this contribution.

2. Some features and performances of the HLD pulsed magnets

Figure 1 shows typical experimental field profiles for several HLD magnets. The KS3 magnet provides up to 71 T in a 24 mm bore with a pulse duration of about 100 ms. The pulse duration can be varied with a crow-bar resistor. The pulse duration of the KS3 can be increased to about 200 ms. In this case the peak field has to be reduced to \( \approx 60 \) T to prevent coil overheating during the longer pulse.

![Figure 1. Time dependence of the magnetic field \( B \) of some HLD coils. The KS3 magnet has achieved a peak field of 71.4 T in a 24 mm bore. For comparison, pulses produced by a 1.5 MJ (KS1, 24 mm bore) and 1 MJ (KS2, 20 mm bore) magnet are also presented. The inset shows the inductance of the KS3 magnet versus pulse energy during coil training.](image)

The most critical point in the coil design and operation is the mechanical stress arising from the Lorentz force. The stress grows as a square of the magnetic field and is of the order of 4 GPa at 100 T. In order to sustain the Maxwell stress we use internal and external reinforcements of the coil winding. The internal reinforcement of every coil layer is based on high-strength fibers which take over a part of the mechanical load from the conductor. The external support also mitigates the stresses in the coil. The application of special high-strength, high-conductive wires, such as CuNb or CuAg, reduces the necessary amount of reinforcement and, hence, allows to increase the current density in the coil. But even the high-strength conductors do not stay in the elastic regime at the peak field. During the first pulses (the so called training) the wire is deformed plastically, increasing the inductance of the magnet (see the inset in figure 1). The mechanical-load cycling causes material fatigue and limits the lifetime of a pulsed magnet. Therefore a careful monitoring of the pulsed-magnet performance is needed in order to predict a magnet failure.

For the fields above 80 T we have chosen a double-coil configuration. Similar multi-coil approaches are pursued in other high-field pulsed-magnet designs [8, 9]. In this case, it is
preferable to extract a high electrical power from the energy supply to reach the peak field before the outer magnet becomes overheated. A high electrical power allows to reduce essentially the size and the weight of high-energy pulsed magnets. The capacitor bank installed at the HLD operates at 24 kV which provides the necessary amount of electrical power. The high operational voltage imposes special demands on the conductors and the coil insulation. As a rule a few layers of polyimide film together with a glass braid are chosen for the wire insulation.

With the HLD design we are trying to achieve higher fields with longer pulse duration and high field homogeneity as well as to provide adequate space inside the magnet for the experimental installations. The designed bore diameters vary from 20 mm for the two-coil 100 T magnet up to 40 mm for the 43 MJ/60 T long-pulse coil. In this way there is enough room to install cryostats such as $^4$He, $^3$He, or dilution refrigerators, in the magnet bore in order to provide the possibility to carry out pulsed-field experiments over a wide temperature range. Our design includes a high-strength insulating tube which forms the magnet bore and protects the experiments from possible electrical hazards (if the magnet fails) and mechanical disturbances during a pulse.

3. FEA analysis

Available simulation tools based on the analytical approach provide useful and reliable results concerning the mid-plane of a coil. As an example, Fig. 2 shows calculated field profiles for the HLD 100 T two-coil magnet and the HLD 60 T long-pulse magnet. The simulation has been done using the PULSE software [6]. However, in many cases one has to go beyond the mid-plane calculation in order to simulate the behavior of the whole coil. The latter can be done using finite-element analysis.

![Figure 2. Calculated field profiles for a two-coil magnet (solid curve) and for a long-pulse mono-coil magnet (dotted curve), both designed at the HLD.](image)

![Figure 3. von Mises stress distribution of the two-coil magnet at the peak field of 100 T. A quarter of the axial cross-section is shown.](image)

One of the main issues addressed in the FEA is the stress distribution caused by Lorentz forces. In order to obtain this distribution a magneto-structural analysis is performed. The task is solved as follows. First, in a linear approximation the magnetic field is calculated and the magnetic forces at each point are derived. Using these forces as an input for the structural task the whole set of mechanical quantities is calculated. This includes all kinds of stress distributions (radial, axial, hoop, von Mises), displacements, and strains. The structural task is essentially non-linear and is solved a by stepwise increase of the load. This nonlinearity comes, first, from non-linear material properties such as elasto-plastic strain-stress dependences of the wires, and second, from contact elements which separate adjacent winding areas inside the coil.
Some results obtained by means of a commercial FEA code, ANSYS Multihpysics, are presented in figure 3. We use a two-dimensional formulation of the problem, where the rotational symmetry of the coil is exploited. We have developed a geometry generation script, which allows for a parametric analysis of coils. Figure 3 shows the calculated von Mises stress distribution inside the two-coil magnet at the peak field of 100 T. The highest stress develops in the internal reinforcement and reaches a value of 3.6 GPa. These results are in qualitative agreement with the stress distribution in the middle plane of the magnet obtained with the analytical approach.

Another important aspect of the magnet optimization is the reduction of cooling time after a pulse. A coil, initially cooled to liquid-nitrogen temperature, heats up during a field pulse adiabatically. The larger the magnet bore, the longer the pulse duration, or higher the field, the more energy has to be supplied to the magnet. As a result the magnet easily reaches temperatures of 300–400 K. In order to reduce the cooling time after each pulse possible rapid-cooling solutions are designed. Among others, special cooling rods or channels will make the cooling process faster by improving the heat transfer from the inner parts of a coil to the liquid-nitrogen bath.

4. Summary
A number of different pulsed magnets have been designed, constructed, and successfully tested at the HLD. First magnets, including 1 MJ/60 T/25 ms and 8.5 MJ/70 T/150 ms mono-coils are operational. Currently a two-coil magnet for magnetic field above 80 T is under construction. Various experimental apparatus are being set up and will be available at pulsed fields soon. Extensive numerical simulations of pulsed magnets support the pulsed-magnet design at the HLD.

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