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Highest Pulsed Magnetic Fields in Science and Technology, Assisted by Advanced Finite-Element Simulations

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Abstract: The generation of high magnetic fields for scientific and industrial applications, in particular by those techniques which meet critical limits of field strength, coil heating, and mechanical stress as well, requires a careful design and modelling based on finite-element simulation. In order to describe the mutual dependence of the electrical, thermodynamical, and mechanical processes in such systems in a reasonable way, the use of multi-physics modules of the finite-element software packages becomes more and more relevant. Here, the designs based on finite-element (FEM) simulations of pulsed magnetic field coils for extreme magnetic flux densities of the order of 100 Tesla as well as pulsed power supplies for the generation of electrical current pulses up to the Mega-Ampere range are presented. A survey on recent technical progresses in science and industry is given.

Keywords: High magnetic fields, pulsed field coils, pulsed power supplies, electromagnetic pulse forming and welding, multi-physics finite element simulation

1. Introduction

High magnetic fields are of essential importance in many research areas and for industrial innovations as well. In consequence, the generation of high magnetic fields emerges to a technology branch of growing relevance. The use of large magnetic fields of up to ~ 1 T (Tesla) is established in many technical applications for many years. Highly polarized permanent magnets for electromotors and generators with high efficiency and large electromagnets for medical diagnostics are only two examples among numerous applications. Nowadays, spectacular and huge coil systems for the generation of even higher magnetic fields up to about 9 T are in use in particle accelerators (e.g. LHC) and up to 14 T under construction for fusion generators (e.g. ITER). In solid state physics, chemistry, and live sciences, strong superconducting magnets up to about 23 T are in widely use combined with a variety of measurement techniques which allow for material characterization and to open new frontiers in science. Power consuming resistive magnets based on the design of Francis Bitter [1] are limited to about 33 T and hybrid coils made of Bitter magnets placed in large superconducting coils are available up to 45 T [2] and will probably never go beyond 50 T due to technical but also financial limits. For this reason, pulsed magnets are brought into the focus of research and industrial applications, in the recent years.

Even more than electromagnets for the generation of static magnetic fields, pulsed magnets are operated under extreme electrical, thermal, and mechanical conditions. High-power magnet pulses lead to a rapid change of the temperature profile, cause huge mechanical loads and plastic deformation, and in combination require a robust electrical insulation due to large electrical field gradients as well. Here, we present two types of pulsed field coils for the generation of very high magnetic fields, one designed for quasistatic (0.01 to 1 sec) pulse-durations (paragraph 2) and a second one for the fast µsec time range (paragraph 3). In addition, we discuss the generation of magnetic field pulses in the µsec time range for industrial forming, joining, and welding processes (paragraph 4). The use of FEM-modeling is an essential tool for a proper design of these field coils and pulsed-power generators.

2. Field Coils for the Generation of Quasistatic High Magnetic Fields

The advances in many fields of solid state physics, such as magnetism, superconductivity, and semiconductivity as well as their impacts in many technology branches, ask for higher and higher magnetic fields. Major breakthroughs in modern research, such as the finding of the Integer and Fractional Quantum Hall Effect [3] have been achieved by doing research in high magnetic fields. Nowadays, fields above 50 Tesla are required in the quasistatic time range, i.e. 0.01 to 1 sec, to solve outstanding problems in physics, chemistry, and live sciences.

Here we present a design of a pulsed magnet developed at the Hochfeld-Magnetlabor Dresden (Dresden High Magnetic Field Laboratory, HLD) located at the Forschungszentrum Dresden-Rossendorf [4]. The coil assembly shown in Fig. 1 served as a development platform for reliable compact magnets which allow for the generation of pulsed fields up to the 70 T range in bore diameters up to 24 mm at a typical pulse length of 0.15 sec. Such magnets are now in use at the HLD for a wide range of experimental techniques, such as electrical transport, magnetization, infrared spectroscopy, electron-spin resonance, ultrasound and others as well. In order to achieve the reliability of a magnet type which is suitable for its operation for user experiments, we have performed FEM simulations which consider the high electrical, thermal, and mechanical loads during the field pulse.

High electrical loads are inevitable to build up a pulsed current needed for the generation of the magnetic field. Both currents (several 10 to 100 kA) and voltages (several 10 kV) are considerably large in pulsed coils for the generation of quasistatic magnetic fields. In the test coil shown in Fig. 1, a pulse current of 23 kA produced by a capacitor bank charged up to 24 kV is used. The voltage between adjacent wire layers can reach values of several kV and therefore requires efficient insulation materials.

The high thermal load results from the enormous pulse energy transferred from the capacitor bank to the magnet, in a time period which is too short for effective continuous-cooling techniques. For a pulse duration of 20 msec, the transferred average power to the test coil shown in Fig. 1 is 75 MW. For this reason, the energy (1.5 MJ) has to be absorbed by the wire windings, and is thus limited by the heat capacity of the wire material. The biggest handicap for pulsed magnets is the immense mechanical load as the consequence of excessive Lorentz forces. Typical mechanical pressures at fields up to 50 T are 1 GPa, i. e. of the size of the failure limit of classical construction material for reinforcement purposes. These loads increase quadratically with the produced magnetic field. For this reason, the wires of pulsed field coils have to be reinforced in- or externally, e. g. by the use of reinforced macro- or micro-composite wires or high-strength fiber materials, such as glass-, carbon-, Dyneema®-, or Zylon®-fibers.

Performing FEM analysis with COMSOL, allows for a simulation of these load scenarios. In particular, the mutual interplay of these loads can also be simulated due to the multi-physics capabilities of COMSOL.

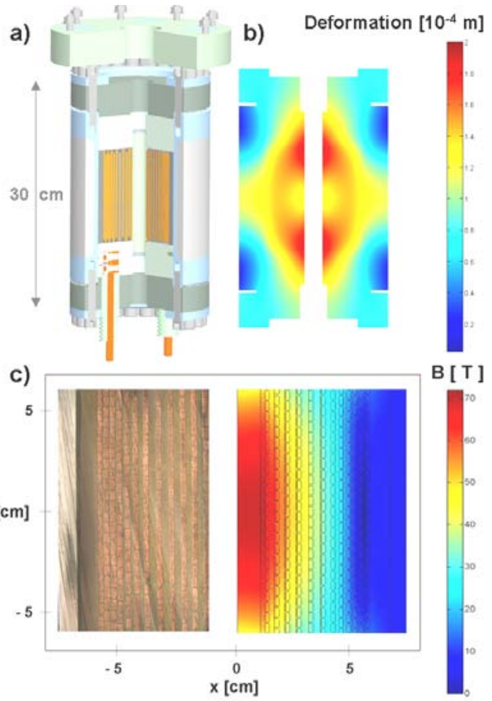

Figure 1. Pulsed magnetic field coil (**a**), mechanical deformation up to 0.2 mm (**b**), magnetic field profile up to 72 T (**c**, right) at the maximum current of 23 kA, and a picture of the wire section of a sliced test coil (**c**, left).

A more detailed report of this magnet design as well as related FEM simulations are published in Ref. [5]. In the recent years, the magnet design has been improved by the high field laboratories in Toulouse, Nijmegen, Oxford, and Dresden in the frame of the design study DeNUF [6] supported by the European Community. In particular, we have focused on the cooling behavior of the magnet. Introducing cooling channels between the winding layers and in the large outer flanges of the magnet, we have improved its cooling time and in consequence the pulse repetition rate essentially. This was also possible by performing a careful FEM study of its thermodynamical properties.

Among the laboratories which focus on the research in high magnetic fields, the user facilities in Los Alamos [5], Tokyo [6], and Dresden [4] currently attempt to extend the field range to 100 Tesla. FEM simulations on such magnet designs play a crucial role for a successful realization of these projects.

3. Few-Turn Coils for µsec Magnetic-Field Pulses of Ultimate Strength

Whereas the magnets described in chapter 2 are operated in a regime which allows for hundreds or more of field pulses, single- or few-turn coils are designed to produce ultimate field strengths beyond 100 Tesla at the expense of their integrity. Their operation is accordingly crude and for this reason asks, prior to the experiment, for feasibility studies based on a full 3D multi-physics simulation comprising electro-dynamics, structural mechanics, and thermo-dynamics. The extremely high pulsed current density triggers a rapid increase of the coil temperature. Although starting from cryogenic conditions, the coil heats up to the melting point if not mechanical destruction due to immense Lorenz forces causes an earlier interrupt of building up the magnetic field. In consequence, the requirements on the experiment and also on the simulation are challenging. Due to the huge warm up during the pulse, all physical quantities are no longer constants but have to be considered as temperature dependent functions. The same is true for mechanical properties which become nonlinear functions of the mechanical stress in the plastic regime. In particular, the modeling of components made of materials with anisotropic physical properties asks for a sophisticated FEM simulation. Although axial symmetry may not be used for a reasonable simulation, the plain geometry of few-turn coils is proving advantageous due to its scalable size which allows for a full 3D simulation.

In Fig. 2 we present a result of the FEM simulation of a five-turn coil designed for magnetic flux densities beyond 100 T. The 3D simulation based on COMSOL considers the influence of the pulse duration and corresponding discharge frequency on the creation of eddy currents in the conductor. The temperature dependence of the electrical resistivity of the used conductor material causes a dynamics through a feedback of the local current density on the magnetic field profile, the local Lorentz force, the local heat-up and other quantities. The FEM simulation in Fig. 2 using COMSOL calculates a magnetic flux density of about 220 T at maximum current I = 600 kA at t = 12 µsec after triggering the high power switch assembly.

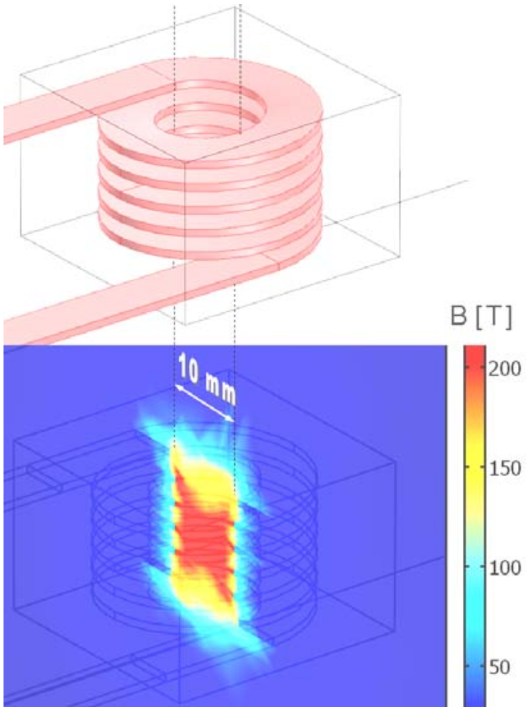

Figure 2. Five-turn field coil and its magnetic field profile at the maximum current of 600 kA during a field pulse with a duration of ~ 25 µsec based on a three-dimensional FEM simulation. The magnetic field is shown in a slice projection where the projection plane is oriented along the z-axis of the coil as well as perpendicular to the connecting current leads.

Further simulations will be performed to evaluate the heat generated in the five turn coil with a small mass of only about 13 g. For this purpose, the high power circuit has to be simulated in addition to the coil. In particular, the electrical resistance as well the impedance of the components are of special interest, as these quantities strongly influence the heat input and dominate the pulse duration, maximum current and maximum field. Using COMSOL, there is a possibility to compute the inductance of power circuit components via an integration of the magnetic energy density.

A review of the technique of single turn coils is given in Ref. 9. Based on this method, a maximum magnetic field of 622 T has been built up at the ISSP, Tokyo [8].

4. Electromagnetic Pulse Forming, Joining and Welding

The first ideas to use pulsed magnetic fields for forming and deforming of metallic work pieces dates back decades (see e.g. Ref. 10), however, the chances to use this technique in an efficiency which qualifies it for wide industrial applications may be given only today. The recent advances on main components, such as powerful capacitors with a high number of discharges during their life time, fast high voltage power supplies for charging the capacitors, and µsec fast switches which allow for discharges up to several 100 kA makes the electromagnetic pulse technology competitive to classical forming and joining techniques. Latest achievements of the method may also be promising to use it for industrial welding processes.

Here we present a result of a FEM simulation using COMSOL which describes the basic principle of electromagnetic pulse forming. In this model, a metal tube is located in the bore of a single turn coil which is connected to a pulsed power supply. The eddy currents induced in the skin depth of the tube flow counterclockwise to the pulse current through the single turn coil and cause by interaction with the magnetic field a Lorentz force which is pointing inside. This is opposite to the expansive force directions in the field coil. Based on that result, by adding the structural mechanics module of COMSOL to the simulation, the mechanical deformation can be computed in detail. There is a large applicability of FEM simulations on electromagnetic pulse forming and joining. Challenging might be the effort to describe electromagnetic pulse welding in addition.

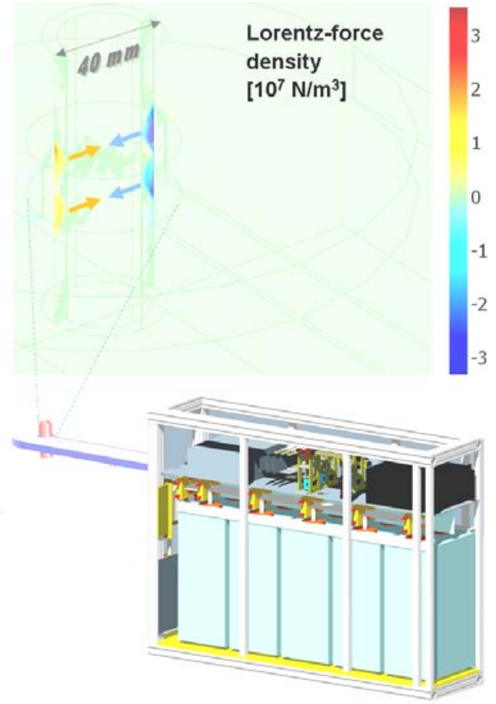

Figure 3. Capacitive pulsed power supply, single-turn deformation coil, cylindrical metallic work piece (red-colored tube), as well as the result of a FEM-simulation of the electromagnetic Lorentz-force density calculated for a current of about 1 MA and a characteristic discharge frequency of 20 kHz. The arrows indicate the compressive force directions in the work piece. For visualization, a slice plot in-plane with the cylindrical axis has been chosen. Compared to the work piece, the Lorentz-force density in the single-turn coil is much smaller and closer to zero on the used color scale.

5. Conclusions

Finite-element (FEM) simulations have emerged to an important tool to evaluate pulsed-power and pulsed-magnetic field techniques which are a technology platform for modern research and novel industrial innovations. Thanks to its stepwise improvement during the recent years, COMSOL offers many features to simulate the physical behavior of even larger structures, such as pulsed magnetic field coils made of various parts of materials or composites with very different quantities. For this purpose, the possibility to perform simulations which comprise several differential equations from many disciplines of physics (multi-physics), such as electrodynamics, mechanics, and thermodynamics is beneficial. COMSOL also allows for a computation of quantities which are associated with the design of electrical circuits, such as the inductance of components without any restriction of their shape. For this reason, COMSOL can be also used to describe pulsed power generators and the technique of electromagnetic pulse forming, joining and possibly welding.

6. References

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