Coil Design for Non-Destructive Pulsed-Field Magnets Targeting 100 T

S. Zherlitsyn, A. D. Bianchi, T. Herrmannsdoerfer, F. Pobell, Yu. Skourski, A. Sytcheva, S. Zvyagin, and J. Wosnitza

***Abstract*—Progress and recent achievements in coil design are presented for the new Dresden High Magnetic Field Laboratory (HLD), which is under construction at the Forschungszentrum Rossendorf. This laboratory is planned to be open for external users in 2007. The facility is placed near a free electron laser which will offer the opportunity to perform infrared spectroscopy in pulsed magnetic fields. Implementation of various experimental techniques, such as transport, magnetization, specific heat, ultrasound, and magnetic resonance in pulsed magnetic fields up to 100 T are planned. Typical pulse durations will be in the range between 10 and 1000 ms with magnet bores ranging from 20 to 40 mm. The pulsed magnets will be energized by a 50 MJ/24 kV modular capacitive pulsed-power supply. With our newly designed coils, so far we were able to reach 65 T in a non-destructive manner. These coils are built using regular copper wire reinforced with an organic fiber (Zylon). Pulse durations for the various coils are between 20 and 50 ms. Different magnet failure modes have been analysed and possible improvements of the magnets are discussed. We also present numerical simulations of our pulsed magnets.**

***Index Terms*—Magnet design and construction, non-destructive pulsed magnet, numerical simulation.**

I. Introduction

NON-DESTRUCTIVE pulsed magnets will play an increasing role for high magnetic field research as they can provide access to the field range between 50 and 100 T, typically for 10–1000 ms, a time which is long enough to carry out most of experiments usually conducted in static magnetic fields. The current record for static magnetic fields is 45 T, achieved at the NHMFL using a hybrid magnet of superconducting and resistive coils [1]. This value is close to the predicted foreseeable limit for static-field magnets of 50 T. In addition, the static-field installations for magnetic fields above 25 T demand a large investment and incur significant running costs. These costs typically exceed the costs of pulsed-field facilities.

The Dresden High Magnetic Field Laboratory (HLD) is targeting at a wide spectrum of research in high magnetic fields and will offer users various experimental techniques, such as transport, magnetization, specific heat, ultrasound, magnetic resonance. The particular feature of this laboratory is the nearby free-electron laser installation which will be used for high-field infrared spectroscopy [2], [3].

The HLD is being equipped with a 50 MJ/24 kV modular capacitor bank [4] which allows operating pulsed magnets with up to four coaxial sections (multi-coil magnet). The capacitor bank will energize five experimental cells with various pulsed magnets. This will include *a*) two 1.4 MJ/60 T small magnets with magnet bores of 20–24 mm, with a typical pulse duration of 25–50 ms; *b*) a 9 MJ/70 T magnet (24 mm bore) with a pulse duration of 100 ms, *c*) a 100 T/10 ms multi-coil magnet with 20 mm bore; *d*) a 43 MJ/60 T long pulse (500 ms) magnet with a bore of 40 mm. Below you will find details on the projected magnets.

The design and fabrication of pulsed-field magnets for the field range of 60–100 T pose a number of material and technological challenges [1], [5]. A pulsed magnet is subjected to extremely high electrical, thermal, and mechanical loads during a field pulse. The high operational voltage of 24 kV of the HLD capacitor bank secures high electric power, but makes it difficult to insulate a pulsed magnet properly. The voltage between adjacent layers in the coil reaches several kilovolts and the electrical insulation inside the coils becomes a serious problem. Below we discuss some possibilities to improve the coil insulation. In addition, a pulsed magnet undergoes a thermal shock during each pulse. Because of Joule heating $Q = \int R(T(t), B(t))I^2(t)dt$ the wire temperature increases from 77 K (initially a coil is cooled to liquid nitrogen temperature) to above room temperature within fractions of a second. One should keep the maximum coil temperature below some limit to avoid destruction of the insulation and reinforcement. The high electrical power of the energy supply gives an opportunity to reduce the field-rise time and, hence, to get the peak field faster than the magnet becomes overheated. But the most serious problem in the pulsed-magnet design is huge mechanical stresses, which arise in the coil at peak field due to the Lorentz force. Since pulsed magnets are operated close to the destruction limit, the magnet design and choice of materials are of crucial importance.

Calculations of the mechanical stresses along with other coil properties can be made using both analytical and numerical approaches. In our calculations we use several software codes (like the PMDS program, developed at the KU Leuven or the codes PULSE and CYCLN developed at the NHMFL). However, the analytical approach is usually applied to the mid-plane of the magnet. These codes do not treat ends of the coil such as flanges or coil connectors. In order to make a reliable coil design, it is

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important to understand how different coil parts function at certain critical locations inside the magnet. The detailed behavior, including heating, cooling and temperature-dependent mechanical properties can only be described by Finite Element Analysis (FEA) that allows simulating the magnet behavior locally. FEA will help to understand and improve the magnet reliability. This is particularly important for large high-energy magnets where destruction tests are not practicable. We use commercial programs like FEMLAB and ANSYS for pulsed-magnet FEA [6].

II. Magnet Design

A. Core Magnet Design

A number of pulsed magnets for different energies, peak fields, and pulse durations are currently under design and construction at the HLD. In order to reduce the total cost and speed up construction of pulsed magnets at the HLD, it seems reasonable to develop a universal core design for the pulsed magnets, which can be applied to various types of projected magnets. Since it is currently challenging to obtain more than 80 T with a mono-coil pulsed magnet, we have tried to develop a magnet design, which could be used both for a mono-coil and as an insert for multi-coil pulsed magnet. It is crucial for multi-coil designs to bring the current of the outer coils closer to the center of the magnet increasing thereby the contribution of the outer coils to the total field of the magnet. That is why we have decided to remove all axial tie rods which are typically used for the axial support of pulsed magnets. Instead, we transfer the axial support of the magnet to a steel cylinder with help of bolts tightening the side flanges. The bolts are directly screwed into the cylinder (see Fig. 1). In this way the axial support of the coil remains strong but it does not increase the coil size in radial direction. It makes the coil compact and saves space for the outer coil. We have named this concept KS ("Kompakte Spule") design. We constructed and successfully tested a number of coils for energies of 1.4 MJ using this concept. Currently a larger 9 MJ coil with a peak field of 70 T and pulse duration of 100 ms is under construction. Fig. 1 shows details of the KS design. The distributed internal reinforcement approach (pioneered by Fritz Herlach at KU Leuven) has been chosen for the HLD magnets. In this approach every wire layer is independently reinforced by fiber composite. Usually the first few layers are mechanically separated with a thin layer of Teflon in order to homogenize the stress distribution in the coil. For the external reinforcement we use a steel cylinder which is shrunk on the winding. The steel cylinder is additionally reinforced by fiber composite from the outside. At present we consider the possibility to use a carbon-fiber composite cylinder instead of a steel one. In this case one could avoid eddy currents in the external reinforcement. Transitions from the winding to the coil connectors are made in a way to reduce the wire bending as much as possible. A wire is placed in a special slit in the G10 composite and clamped directly to the connector at the end. There is also a separate robust construction, which provides a transition from copper connectors to coaxial current leads.

The magnet is mounted with the connectors from the bottom side. This provides extra space for the scientific experiments on the top side of the magnet.

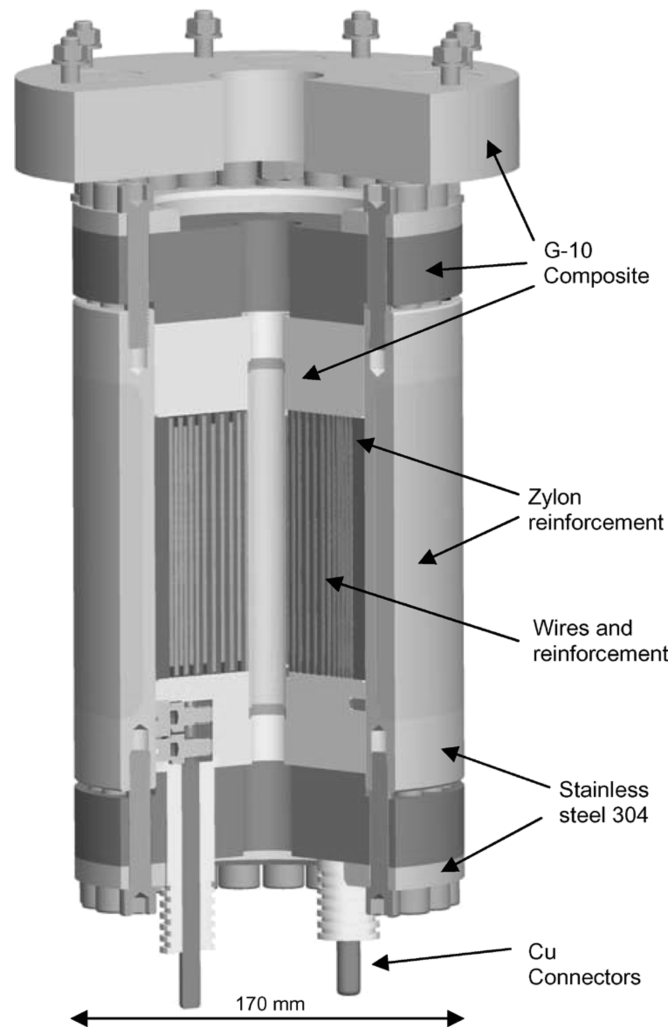

Fig. 1. Core design of the pulsed magnets at the HLD. The outer diameter is given for the KS2a/65 T/20 ms coil. The magnet bore in this case is 20 mm. The coil inductance is 2.3 mH.

B. 60 T Pulsed Field Magnets in KS Design

Using the magnet core design described in section A, we have constructed a number of magnets for fields between 60 and 65 T. For these magnets we used ordinary copper wire with a cross-section of $2 \times 4\ \mathrm{mm}^2$ insulated with Kapton film. In order to provide good wire insulation, the Kapton film should be well fused to the wire. The typical magnet (for instance KS2a, see Fig. 1) could provide fields up to 65 T (see Fig. 2). The magnetic field can be measured with a Hall-probe [7] and a pick-up coil. The KS2a magnet has 12 wire layers, reinforced by a Zylon-Stycast 1266 composite. The filling factor of the Zylon fiber in the composite is approximately 80%. In case of the KS2 magnets the peak stress in the Zylon fiber of the internal reinforcement reached a level of 3.2 GPa. This is almost the same stress level which we plan for a 100 T magnet. We have tested our first magnets to destruction in order to elucidate weak features of the design. Usually we observed sharp spikes in the pick-up coil signal a few pulses prior to the destruction of the coil. We assume that these spikes are associated with partial discharges in the coil from small damaged sections of the wire insulation. Indeed, the post-mortem analysis showed that the main reason

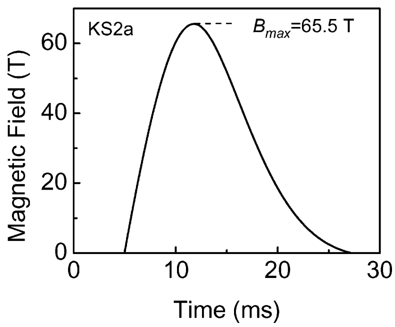

Fig. 2. Measured magnetic field versus time in the KS2a coil with a peak current of 23 kA.

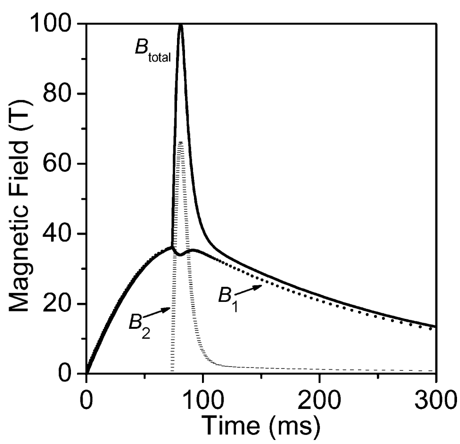

Fig. 3. Time profiles of magnetic fields B_1 (dotted line) and B_2 (horizontal bar line) in the outer and inner coils, respectively, contributing to the total magnetic field $B_{\rm total}$ (solid line) for a two-coil 100 T magnet. Calculations have been made with the PULSE code.

for the magnet failures was the mechanical destruction of the wire insulation. As result, the turns in middle layers in proximity of the magnet flanges are shorted electrically. Often the fault was located at a wire transition from one layer to another. Rings made from G10 composite which support a wire at the transition and the addition of a braided Zylon sleeve to the wire have dramatically reduced these problems.

Thanks to significant improvements, the KS21a magnet (made using ordinary copper wire) has passed 10 pulses above 60 T without any sign of partial discharges. The total inductance change of the magnet was below 1% and saturated after a few pulses. We plan to use this type magnet as a 60 T user magnet for scientific experiments at the HLD.

In the next step we are going to use high strength wires like Glidcop AL60, copper stainless steel and CuNb for the construction of future KS2 magnets.

C. 100 T Two-Coil Magnet

Our calculations show that with the currently available conductors and reinforcement the 100 T magnet cannot be built with one section as a mono-coil in a practical way. One option is a two-coil magnet with the inner section entirely based on the KS core design (see above). This section should provide a magnetic field of 65 T using 3 MJ. The outer section, fed by a 43 MJ energy supply should produce a 35 T background field (see Fig. 3) in a bore of 225 mm.

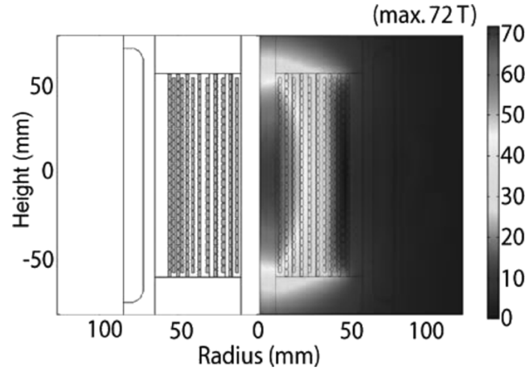

Fig. 4. The left side of the figure shows the structure inside a KS2 magnet in a cut through the axis of the magnet. The wires are in red. The color-coded plot at the right shows the magnetic flux density in Tesla in the same plane generated by the peak-current of 23 kA. Lower fields are in blue, higher fields are in red with the maximum of 72 T in the center of the magnet.

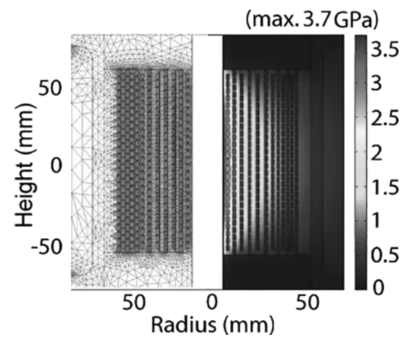

Fig. 5. The left side of the figure shows with gray lines a triangular mesh spanned over the spatial domain with KS2 magnet used in the FEA simulations. The right side shows the calculated Von Mises stress distribution developing inside the magnet at the peak field of 72 Tesla on a color-coded plot in units of GPa. Blue corresponds to lower stress and red to higher. The highest Von Mises stress of 3.7 GPa is found in the most inner layer of reinforcement.

CuNb wire with a cross-section of $6 \times 4\ \mathrm{mm}^2$ and a UTS of 1.1 GPa will be used for the inner coil of the magnet whereas the outer coil will be wound with $8 \times 14\ \mathrm{mm}^2$ copper. The internal reinforcement of both coils will be based on Zylon composite. The stress level in Zylon fiber is predicted to be 3.5 GPa.

III. Finite Element Analysis of KS Magnet

The design of non-destructive pulsed magnets demands an extensive modelling of various aspects of the pulsed-magnet behavior. Modelling requires a solution of nonlinear partial differential equations. Usually a two-dimensional model is a good approximation for a pulsed magnet. However, some critical parts of the magnet can be modelled only in three dimensions. Examples are layer transitions between wire in the coil and the electrical connectors of the magnet. Even in two dimensions a magnet modelling task is not trivial. The Lorentz forces during a field pulse are very high, trying to tear the magnet apart. The stresses associated with the Lorentz force drive the wire into nonlinear plastic regime. In addition to extreme mechanical loads, the magnet undergoes a thermal shock at every pulse. Moreover, there are a number of effects (like eddy currents, magnetoresistance, thermal, and some mechanical effects), which cannot be analysed within the static approach. One should consider a dynamical model in order to get a realistic picture of pulsed magnet behavior. All these problems can be addressed with the FEA.

FEA usually demands extensive computer calculations. FEA produces solutions of partial differential equations locally everywhere in the magnet. Magnetic field distribution for the KS2 magnet calculated with FEA is shown in Fig. 4. Using this result as an input data for the next step, one can calculate the spatial stress distribution inside the magnet (Fig. 5). Note, that the measurement of the field profile in Fig. 2 has been done on a magnet with a different winding geometry compared to the geometry used in the FEA calculations used in Figs. 4 and 5. FEA delivers very useful information for the magnet design (for example, on the mechanical stresses, magnetic fields, temperature, and eddy currents in the coil). It is crucial for FEA to have reliable input data of the material properties used in the simulations. Thus, we have started to investigate physical properties of materials related to the magnet design and are developing a data base. 3-D simulations and fatigue study of the magnets will also be addressed in our study.

IV. Conclusion

We have developed a core design for non-destructive pulsed magnets which could be used both for mono-coil and multi-coil magnets. The main principles of this design have been proven successful for 60 T coils. First user coils have been constructed. This design will be used for a 100 T magnet prototype soon.

At the HLD we use FEA simulations as integral part of designing pulsed magnets. We consider FEA simulations to play an important role in future magnet design development.

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