Status of the Pulsed-Magnet-Development Program at the Dresden High Magnetic Field Laboratory

S. Zherlitsyn, B. Wustmann, T. Herrmannsdörfer, and J. Wosnitza

Abstract— **The Dresden High Magnetic Field Laboratory (HLD) is a pulsed-field user facility which offers to researches a variety of experimental techniques combined with non-destructive pulsed magnetic fields. Recently a new, 9.5 MJ dual-coil magnet has been commissioned. This magnet has achieved magnetic field of 91.4 T in a 16 mm bore and it is available for users now. In this paper, we report on some key upgrades in the magnet design which have led to breaking the 90 T limit at the HLD. Further possible design improvements are discussed. In addition, we share our operational experience obtained with the pulsed magnets.**

***Index Terms*— Non-destructive pulsed magnet, magnet design and construction.**

I. INTRODUCTION

Pulsed magnets offer important extensions of the static magnetic fields range for many experimental investigations. Together with some well-established experimental techniques, such as electrical transport, magnetization, ultrasound, magnetostriction, electron spin resonance, and high-field infrared spectroscopy several less typical pulsed-field experiments such as nuclear magnetic resonance or specific heat are also emerging at the HLD now [1]. Some specific magnet characteristics such as low vibrations, low electrical noise, available experimental space and magnetic field homogeneity alongside with the used data-acquisition equipment play a crucial role for the experimental data quality. Together with the peak field these characteristics are central topics for pulsed-magnet designers. In addition, magnet reliability, longevity, and magnet-cooling time are important issues which essentially affect the user operation. A high-power, 50 MJ modular capacitor bank at the HLD [2], with a maximum charging voltage of 24 kV offers a flexible background to design compact, high-performance pulsed magnets. For more details on a typical magnet design developed at the HLD see Refs. 3 - 5. In Ref. 3 we reported on achieving 87.2 T in a 20 mm bore by use of a 9 MJ dual-coil magnet. The design of this magnet has been improved mainly by optimizing the inner reinforcement system and by reducing the magnet bore down to 16 mm. This magnet has delivered a world-record magnetic flux at a flux-density as high as 91.4 T offering sufficient space for many potential experiments. It is routinely operating now providing up to 87 T for user and in-house research.

II. 90 T PULSED MAGNET

The success in obtaining magnetic fields beyond 90 T is based on a long magnet-technology development carried out in various laboratories and going back to the first half of the last century (for earlier reviews see Refs 6 and 7). Numerical simulations play an important role in the pulsed-magnet design allowing to study the processes occurring in pulsed magnets. We are using the PULSE and CYCLN codes from the National High Magnetic Field Laboratory (Tallahassee, USA) [8], the PMDS program, developed at KU Leuven in cooperation with scientists from HUST (Wuhan, China) [9] as well as commercial finite element analysis (FEA) software [10]. However, it is necessary to emphasize that the simulations, although providing valuable information for magnet designers, can only help to some extent. A pulsed magnet has a complex structure which is challenging to model. In addition, it is hardly possible to feed the models with realistic (sometimes not well-known) material properties. As a result, the simulation outcome (particularly in case of FEA) can strongly deviate from reality. Further, it is not straightforward to take into consideration some dynamical effects arising in the magnet. That is why a very important step in the magnet design process is to test pulsed magnets to destruction, to analyze the failure mode, and to introduce corresponding improvements in subsequent coils. Some results of this procedure are reported in this paper.

The codes mentioned above can adequately model the middle plane of the magnet helping to optimize the internal reinforcement distribution [11]. It is also clear from this kind of simulations, that the most practical way to reach magnetic fields above 90 T is a multi-coil configuration with the possibility to use different wires and separate energy suppliers for each subcoil [12-16]. We use a dual-coil configuration, as the simplest option to go beyond the 90 T level. The principal magnet design has been described in details earlier [3]. In an attempt to increase the magnetic field from 87 to 91 T we reduced the magnet-bore size from 20 to 16 mm. Analyzing the failure modes for similar dual-coil prototypes we had noticed that the main problem appears to be an instability of the thick layers of internal Zylon reinforcement [17] against

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the shear and axial stresses. This instability always developed in the inner subcoil, near the winding edges usually somewhere between the third and sixth wire layer. In this area some cracks propagate through the reinforcement layers emerging as cone-like structures from the wires. Some wires became even displaced from their original positions demonstrating local elongation and thinning. In some cases, a significant axial movement of the layer-to-layer transition windings has been observed. This evidenced that the thick Zylon reinforcement optimized for the radial Lorentz force in the middle plane, can not sustain the axial and shear stresses near the winding edges. Undoubtedly, the axial coil compression during the pulse and the concomitant gap between the magnet flanges and the coil winding add to the problem. That is why step-like flanges had been introduced in an attempt to improve the joining to the windings. Unfortunately, this attempt was unsuccessful since the area between the flanges and the windings effectively increased resulting in a worsened connection. In another attempt, we combined stainless-steel foil with the Zylon reinforcement (similar to the reinforcement system reported in Ref. 12) in order to stabilize mechanical stresses near the winding edges. This works successfully for a 65 T monocoil, but it was not sufficiently effective for a dual-coil magnet for magnetic fields above 80 T.

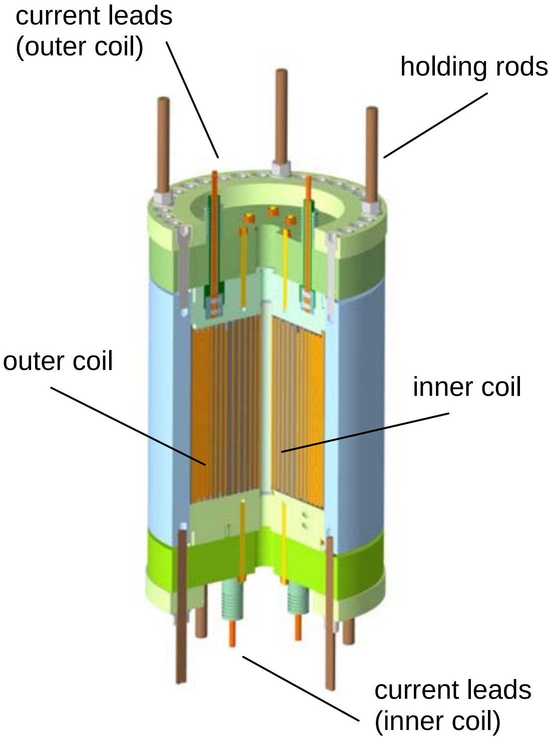

Fig. 1. (Color online) 90 T / 9.5 MJ dual-coil magnet (see text for details). This magnet has an outer diameter of 320 mm and a total weight of approximately 200 kg. This magnet has produced a magnetic field of 91.4 T in a 16 mm bore (see magnet B in Fig. 2).

Instead of the stainless-steel foil we are using an S2-glass fabric in combination with the Zylon fiber now. This combination brings some important advantages stabilizing the thick reinforcement layers and helping to redistribute the mechanical stresses in the reinforcement. The internal reinforcement contains more S2-glass fabric near the edges whereas the Zylon fiber prevails in the middle of the coil. In addition, improved G10 reinforcement transition rings have been designed to support the wire transitions.

Here, we provide some more technical details of the 90 T magnet (see Fig. 1). The inner six layers of the coil are wound using CuNb wire [18] with a cross-section of 2.8 x 4.3 mm^2. Wieland-K88 [19] wire with 4 x 6 mm^2 cross-section is employed for the outer ten layers of the magnet. Both wires are insulated with Kapton foil and the insulation is additionally protected with an S2-glass–Zylon braiding. The Kapton foil together with the braiding layer gives an undesired dimension increase of 0.4 mm per wire side, but provides a very robust electrical insulation. The magnet has an outer diameter of 320 mm and a total weight of approximately 200 kg. The inner subcoil of the magnet is energized by a 0.92 MJ/100 kA capacitor module and the outer subcoil is connected to 8.6 MJ from three 2.88 MJ modules of the HLD capacitor bank [2]. The cooling time of the magnet is between 3 to 4 hours.

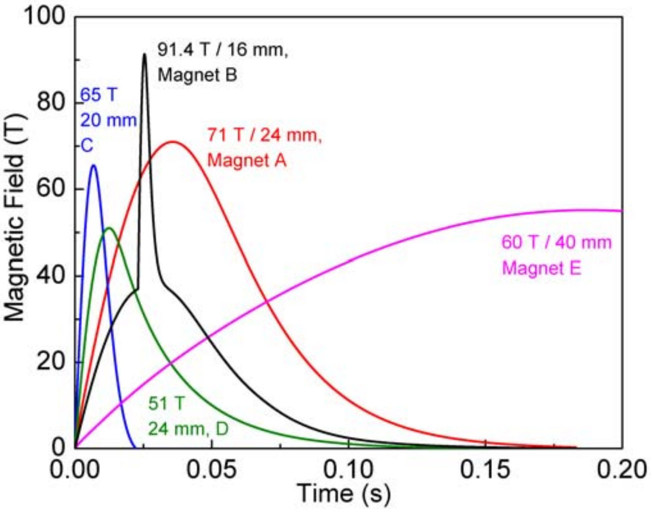

Fig. 2. (Color online) Measured time dependences of the magnetic fields obtained with various pulsed magnets operational at the HLD. Magnets A and D are 8.5 and 1.5 MJ magnets, respectively. Both of them have bores of 24 mm. Magnet B is a dual-coil 9.5 MJ magnet with a 16 mm bore. Magnet C is a 1 MJ pulsed magnet with a 20 mm bore. Magnet E is a 43 MJ long-pulse magnet with a 40 mm bore.

The pulse shape for the dual-coil magnet is shown in Fig. 2 (magnet B). The estimated maximum stress in the middle plane of the magnet is about 3.4 GPa at the peak field. After a number of pulses at the level of 85 – 91 T no significant change in the magnet inductance has been detected. The initial magnetic-field calibration obtained with a Hall sensor and a pick-up coil (see Refs. 3 and 20 for details) has been confirmed by Shubnikov – de Haas measurements of a high-temperature superconductor. As an additional improvement of the magnet design we are going to decrease the eddy-current losses by optimizing the geometry of the metallic parts and to apply more axial pre-stress in the region of the magnet bore. The former will allow for slightly larger peak fields and the latter will help to stabilize the inner subcoil, by reducing the gap between the windings and the end flanges. In order to reach even higher magnetic fields we are considering the possibility to reduce the magnet bore size, keeping the main features of the existing dual-coil design unchanged.

III. MONO-COIL PULSED MAGNETS

Together with the 90 T dual coil the HLD operates a number of mono-coil pulsed magnets ranging from 1.5 MJ / 65 T short-pulse to 43 MJ / 60 T long-pulse magnets. Fig. 2 shows magnetic-field pulses versus time for various HLD magnets. The design of these magnets has previously been reported in Refs. 3 - 5. Most of these magnets have demonstrated their excellent performance and outstanding longevity. For instance, the magnet C has delivered more than 5000 pulses with more than 2000 pulses above 80 % of peak field. The magnet A has delivered approximately 2000 pulses with 600 pulses close to the peak field.

IV. CONCLUSION

We have reported on the current status of the pulsed-magnet development program at the HLD. A dual-coil 90 T magnet is operational now. Some improvements have been planned for this type of magnet that includes a reduction of the eddy-current losses and an increase of the axial pre-stress in the magnet. In addition, a number of mono-coil pulsed magnets provide reliably high magnetic fields at the HLD. We proceed further with the magnet-technology program to reach magnetic fields beyond 95 T.

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