Elements of pulsed magnet design

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Abstract. The design of pulsed magnets is discussed on basis of calculations with the PMDS code (Pulsed Magnet Design Software), both for coils with constant winding density and with optimised internal reinforcement by fibre composites. The importance of determining material properties is pointed out, and a proposal is made for the development of a system that allows measurement of material properties under realistic conditions as they are present in pulsed magnets.

1. Currently used design schemes of high performance pulsed magnets

Presently, the majority of pulsed magnets is made according to two different schemes. The first scheme, inspired by the ground-breaking work of Foner [1], combines strong wires containing micro-(or nano-)filaments with external reinforcement by metallic shells and sometimes internal reinforcement by one or more metallic cylinders [2]. Kindo obtained the highest fields with coils of this type [3]. Similar coils were made at the Clarendon Laboratory, Oxford [4] and the LNCMP Toulouse [5], mostly with copper wire reinforced by a stainless steel mantle, developed at Oxford and now also manufactured at Toulouse. The second scheme was developed at K.U.Leuven [6]; this is internal reinforcement by fibre composites of variable thickness such that the stress is evenly distributed over the entire coil, combined with external reinforcement by fibre composites (usually carbon fibre). This scheme combines superior efficiency with ease of construction, it has therefore been adopted by most pulsed field laboratories, and coils of this type are commercially available [7].

2. Calculation of stresses and heating

For basic coil design, it is sufficient to calculate stresses and heating in the mid-plane of the coil where they are highest. For coils with constant winding density, analytical calculations [8, 9] are adequate in principle. The dimensioning of coils with optimised internal reinforcement requires numerical calculation. To this end, at K.U.Leuven two codes were developed that run on a PC with a typical running time of less than one minute. The first code, PMDS1, was developed by Liang Li [6, 10], this solves the coupled differential equations for the stress distribution by matrix inversion; current distribution and coil heating are calculated by solving the differential equations for the diffusion of magnetic flux. The calculation is incremental: the field is increased in small steps and the equations are adapted when plastic deformation is encountered. The second code, PMDS2, is under development in the context of a bilateral project Flanders-China [11]. It has been adopted as a design platform in the European pulsed field project DeNUF [12]. This code calculates stresses by total strain theory, and heating with the eddy current approximation for the skin effect, for capacitor discharges as well as for controlled waveforms. The anisotropy of fibre composites is taken into
account, and the user-friendly visual BASIC interface for design and graphic presentation has been greatly enhanced, with a database that can be easily adapted to include new data items as they are needed and become available. This code allows calculation of dual coil systems and the effect of a conducting cylinder. Commercially available finite element codes like ANSYS [13] or FEMLAB [14] can calculate with more detail, at the expense of running time and preparation. For exploratory work and for the design of compact coils, PMDS is adequate and much more convenient. An interface for easy transfer of all coil data to ANSYS is included.

3. Results of stress calculations and design guidelines derived from these

The performance of coils with constant winding density depends mostly on the properties of the wire, in principle it is not necessary to calculate the stress distribution in detail. In particular, Kindo designs his very successful coils merely by intuition, including the dimensioning and placement of internal reinforcing metallic cylinders. Figure 1a shows the stress distribution in a coil design with constant winding density, calculated by PMDS2.1 with allowed separation of the layers. The copper wire with stainless steel mantle was manufactured at LNCMP (Toulouse) and the properties have been measured [15]. In order not to overload the graphs, only the critical von Mises stress and the radial stress are shown. At 55 T, the peak von Mises stress is 1.1 GPa while the ultimate tensile stress (UTS) of this particular wire is 1.26 GPa and the elastic-plastic limit is about 0.85 GPa. If separation of the layers is not allowed, the peak stress is 1.1 GPa at the inner radius already at 40 T. One could argue that layers will separate anyhow under the influence of the tensile radial stress, but it should be noted that this stress is quite small and may not be sufficient to cause separation. Therefore it would be advisable to insert thin layers or coatings that facilitate separation. In addition, it is recommended to insert a thin insulating layer e.g. a glass fibre cloth between layers in order to improve insulation. In figure 1b, fibre reinforcement has been added in a coil with the same wire and approximately the same dimensions. At 65 T, peak stress in the wire is now 1 GPa, and in the Zylon it is 1.6 GPa (UTS > 3 GPa). In the outer section with glass fibre reinforcement, adding the external reinforcement with carbon fibre composite reduces the highest peak stress in the wire by 0.3 GPa at the division between the inner and outer section. This coil has 14 layers of wire vs. 20 layers in the coil without reinforcement, for the same heating the pulse duration will thus be shorter by a factor of 0.7.

Figure 1. Stress distribution in a coil design with copper wire clad by a stainless steel mantle (wire manufactured at Toulouse), calculated with PMDS2.1. Left graph (a) with constant winding density, right graph (b) with internal reinforcement by Zylon composite (inner section – stress higher than in wire) and S-glass fibre composite (outer section – stress lower than in wire).

Figure 2 deals with the stress distribution in coils with internal reinforcement. For these coils it is well known that layers ought to separate. Figure 2a shows the effect of using soft copper in the outer...
section of the coil shown in figure 1b. This coil will be electrically more efficient. The copper undergoes plastic deformation; with many successful user coils it was demonstrated that this can be tolerated. The thickness of the outer carbon fibre reinforcement is increased in order to support the transmitted radial stress. Figure 2b demonstrates the influence of the anisotropy of the composite in a coil that was tested at Leuven up to 77 T (optimised under the assumption of isotropy and UTS of ~3 GPa; in the direction of the fibres the UTS of the Zylon composite is ~6 GPa). For Zylon, the elastic modulus in the direction of the fibres is 230 GPa, in the perpendicular direction values between 3 and 10 GPa have been quoted. With decreasing perpendicular modulus, the stress increases more steeply toward the inner radius. This imposes a limitation on internal fibre composite reinforcement: if layers are made very thick in order to support higher stress, this is defeated by the steep increase of stress toward the inner radius. Another important point is matching the ultimate elongation of the fibre composite and the wire. For example, S-glass fibre has an elongation at UTS of 3.7 %; this is more than the permissible elongation of strong conductors and thus the strength of glass fibres cannot be fully exploited in this combination. Carbon (1.2 %) and Zylon (1.4 %) are better suited; these fibres also are stronger. Zylon does not impregnate well with epoxy, in particular under vacuum because of the high winding density. Feasibility tests with small models at Leuven have shown that flow-through impregnation under relatively high pressure (of order 5 bar) is possible. Coils with soft copper and vacuum-impregnated glass fibre have gained a reputation as reliable user coils.

![Figure 2](image)

Figure 2. Stress distribution in coils with optimised reinforcement by fibre composites. Left graph (a) is the coil of figure 1b with soft copper and glass fibre in the outer section, right graph (b) shows the effect of the anisotropy of fibre composites in a coil with soft copper wire and Zylon; curves are shown assuming isotropy at 230 GPa (bold), and for a perpendicular modulus of 10 (dots) and 3 GPa.

Figures 1b and 2 demonstrate a typical feature of internally reinforced coils. There are two clearly distinguished regions: in the inner region, wires separate from the underlying fibre layer (in practice, this is facilitated by thin layers of Teflon tape); in the outer region, the radial stress is compressive and it is transmitted to the external reinforcement that is needed for confinement. In this region, optimisation is not feasible by making the reinforcing layers so thin that they would support the maximum possible stress. Glass fibre is used in this region mainly for better electrical insulation.

The insulation of the wires is not yet taken into account in stress calculations for the simple reason that the mechanical properties of this insulation are not adequately known, if at all. However, for a wire with e.g. 2 mm thickness and 0.1 mm insulation (on each side) this amounts to 10 % of the volume and therefore it is certainly not negligible.

Since around 1990, the design of non-destructive 100 T user coils is pursued at several laboratories. Two dedicated workshops were held at Leuven, a white book on “100 tesla science” was published by the European Science Foundation, and there was a sequence of EU-sponsored feasibility and design
So far, the highest user fields of order 75 T were achieved by the dual coil system of the European “ARMS” project [16], and by a monolithic coil made at NHMFL [17]. By optimistic interpretation of the scarce materials data, it is possible in principle (but still marginal) to design 100 T coils on the computer. However, it is evident that very large efforts are still needed for the practical realization; these efforts ought to be justified by substantial gains in scientific research. The 100 T mark represents a ceiling, thus development will become increasingly difficult as this is approached.

4. A new system for determining material properties and testing new design features.

Even the most sophisticated codes cannot give reliable results as long as material properties are not known with adequate precision. At present, very little is known about material properties under the conditions that are present in a pulsed magnet, i.e. rapidly varying temperature down to 77 K and pulsed loading in cylindrical symmetry (ordinary tensile tests are always done under static conditions and in linear geometry). The best approximation available so far is the “explo-vessel”, a copper cylinder on which the specimen is wound and which is slowly expanded by hydraulic pressure [16]. We propose a new method of dynamic testing under realistic conditions that is based on the fact that the inner layers of a coil separate from each other under pulsed field loading. The proposed testing station is a dual coil system where the outer coil provides a field of 40-60 T in a bore of order 30-40 mm. The specimen under test is in the first place a coil with two layers (for convenience of contacting from one side) that is inserted into this background field and energised by a separate small capacitor bank; a specimen with one layer is feasible where one of the current leads is a cylinder with axial slits. The free space between the inner and the outer coil provides convenient access for diagnostic instrumentation such as fibre optics with integrated diffraction gratings. The outer coil ought to be protected by an adequate shield against explosion of the inner coil such that the inner coil can be tested to destruction; the field at which destruction occurs and post-mortem analysis provides the ultimate data point. This system will permit efficient testing of both material properties and design concepts; including the important properties related to material fatigue.

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