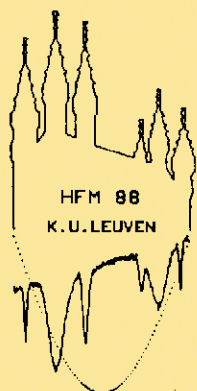


High Field Magnetism

Proceedings of the 2nd International Symposium on
High Field Magnetism
(including a Review of High-Field Facilities Worldwide)
held in Leuven, Belgium, 20–23 July 1988



Editors:

F. Herlach
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HIGH FIELD MAGNETISM

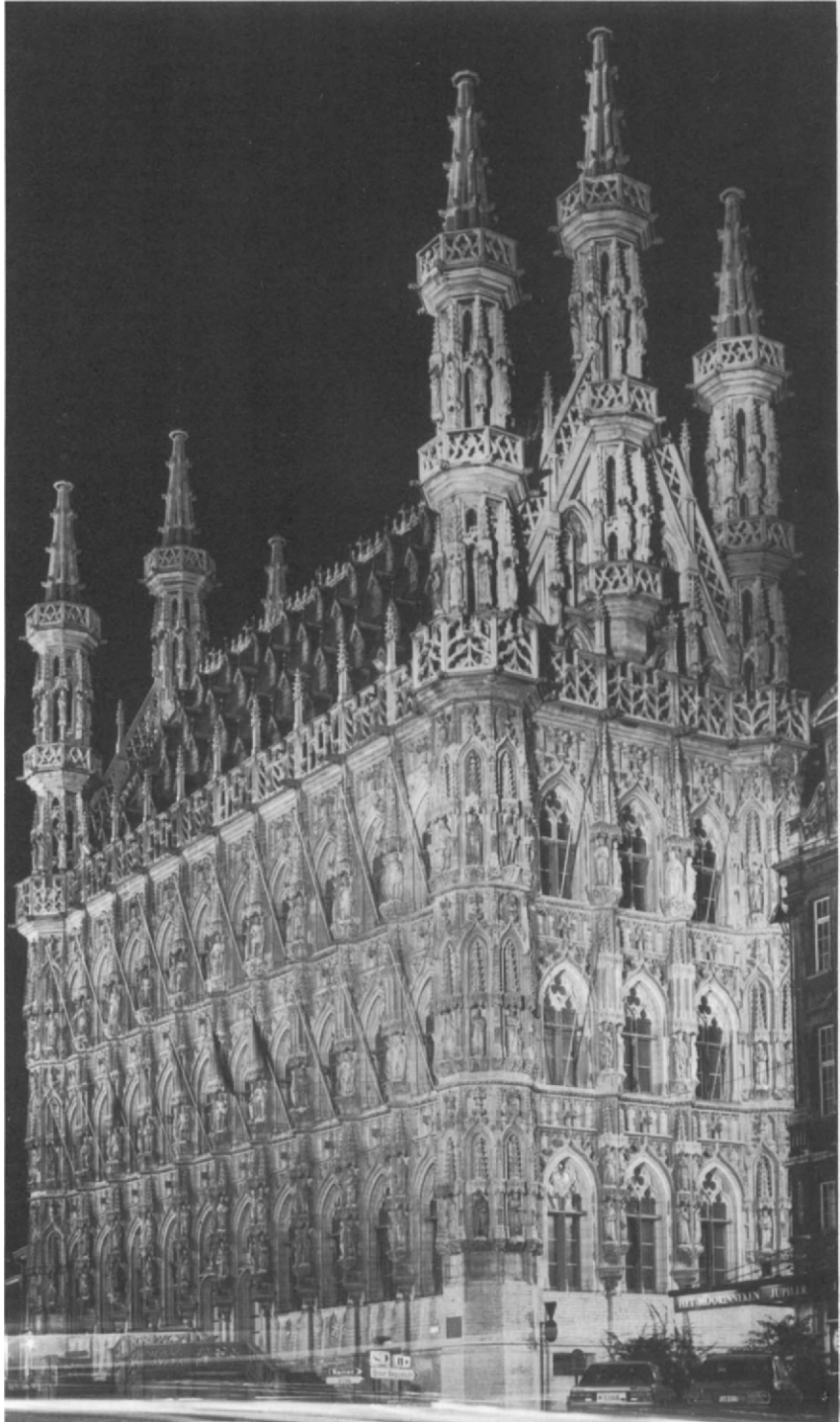
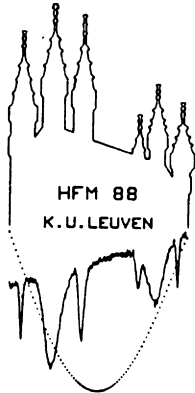


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Proceedings of the 2nd International
Symposium on High Field Magnetism
Leuven, Belgium, 20–23 July 1988



Editors:

F. Herlach

*Katholieke Universiteit Leuven
3030 Leuven, Belgium*

J. J. M. Franse

*Universiteit van Amsterdam
1018 XE Amsterdam, The Netherlands*



1989

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PREFACE

The first International Symposium on High Field Magnetism was held on September 13–14, 1982 at Osaka [Proceedings: “High Field Magnetism”, ed. M. Date (North-Holland, 1983)]. Besides magnetism in very strong magnetic fields, it covered the topics of high field superconductivity and the technology of laboratory magnets. Inspired by the success of the first symposium, we called the second one as a satellite meeting to the International Conference on Magnetism (ICM) held at Paris (July 25–29, 1988). The same topics were covered and the duration was extended to four days.

The first day was dedicated to an associated Symposium on Laboratory Magnet Technology, with five invited papers covering the entire field range from dc fields to explosively generated megagauss fields. All major magnet laboratories presented their facilities with poster presentations, exhibits and video; these exhibits remained on display throughout the conference. This part of the symposium was concluded with a workshop on the development of magnet laboratory facilities.

In the remaining three days, 70 papers were presented on a broad range of topics from magnetism to superconductivity, the latter mostly on the new high temperature superconductors. However, the continuing importance of Chevrel phase superconductors was underscored in an invited paper. A particular milestone is the experimental observation of an upper critical field of the order of 100 T in Y–Ba–Cu–O.

Magnetic properties of solids have been reported for a variety of materials including the hard magnetic materials of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ type and the heavy fermion systems. Magnetic fields of the order of 100 T are required for investigating the magnetic properties of f-metal compounds because of the extremely large values of the anisotropy fields present in most of these materials. In d-metals, a problem of peculiar interest is the metamagnetic transition in YCo_2 and related compounds that takes place in magnetic fields of the order of 100 T.

Semiconductors in strong magnetic fields are covered by another series of conferences; the most recent one was held at Würzburg (August 22–26, 1988; G. Landwehr). We included semimagnetic semiconductors and one general lecture on recent advances in semiconductor physics.

One remarkable trend has emerged at the present symposium: 65% of the experimental papers involve pulsed magnetic fields, indicating that this elegant and economical technique, pioneered by P. Kapitza half a century ago, is now gaining wide acceptance. Prospects for the future look promising as it was demonstrated in several contributions that the common limit of 45 T for nondestructive pulsed fields is now pushed into the 60 T region.

In conclusion, thanks are due to the participants as well as to members of the Laboratorium voor Lage Temperaturen en Hoge-Veldenfysika and the Physics Department of the University of Leuven for the excellent cooperation which resulted in a pleasant and efficient conference. Financial support was provided by the Belgian Nationaal Fonds voor Wetenschappelijk Onderzoek and Ministerie van Onderwijs and by the Onderzoeksraad of the Katholieke Universiteit Leuven.

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CHAPTER 1

MAGNET TECHNOLOGY

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D.C. LABORATORY ELECTROMAGNETS

H.-J. SCHNEIDER-MUNTAU

Hochfeld-Magnetlabor Grenoble des Max-Planck-Instituts für Festkörperforschung, Stuttgart, Fed. Rep. Germany

A review is given of the present possibilities to generate continuous magnetic fields above 20 T by means of resistive, water cooled coils, most advantageously by polyhelix magnets. The record field of 25 T was achieved with a resistive magnet that utilises this new technology. Today the highest continuous field of 31.4 T is produced at Grenoble with a hybrid magnet which consists of an inner resistive part (polyhelix and Bitter) and an outer superconducting coil. The advantages of polyhelix magnets are discussed and an outlook on future developments is presented.

1. Introduction

There are two magnet laboratories in the world that possess a power supply of 10 MW, the power required to generate, with resistive, solenoid type magnets, continuous fields well above 20 T.

The Francis Bitter National Magnet Laboratory at Cambridge, U.S.A., has had since 1963 four motor generators with a combined rating of 10 MW continuous and 12 MW for 15 minutes. Several magnets were built to generate fields above 20 T, the famous 1J achieved 23.8 T in a room temperature bore of 32 mm, consuming 10.5 MW [1]. In the last years it was improved to 24 T, which seems to be the upper limit for Bitter magnets. There was also an attempt to use the overload capability of the generators to obtain even higher fields. Montgomery [2] built a magnet which was to generate 25 T in a 50-mm diameter bore with 16 MW of power for a few minutes. However, imperfect distribution of the cooling water led to burnouts of the inner coil of this three-coil magnet.

The High Field Magnet Laboratory of Grenoble, run jointly by the C.N.R.S. and the Max-Planck-Institut für Festkörperforschung, also has a power supply of 10 MW, consisting of four identical solid-state silicon-controlled rectifier

units with no overload capability. The first magnets built were Bitter magnets [3], because this construction technique is well established and documented. It was soon realised that these magnets have an upper limit of about 21 T in 50 mm diameter (corresponding to 24 T in 32 mm), beyond which the two main constraints, heat flux and stresses, limit performance and longevity dramatically. A new technique for building magnets, the so-called polyhelix magnets [4], was therefore developed. The inner, highly stressed part consists of a set of concentric monolayer coils, each designed for the same and maximum admissible hoop stress. The outer background field is generated by six radially and axially optimised Bitter stacks. The five years of effort for developing this new technology was crowned by the achievement of a record field of 25 T in a 50 mm diameter bore with a power consumption of only 10 MW, still unrivalled since 1982.

Because of the advantage of reduced induced hoop stresses and the fact that the realignment forces are much smaller than with Bitter magnets, polyhelix magnets are ideal for hybrid magnets. The Grenoble hybrid magnet uses a polyhelix insert. It generates the highest continuous field of 31.4 T in a 50-mm diameter room temperature bore.

2. Resistive magnets

An efficient radial current density distribution, i.e. one that generates the highest field for a given

power, concentrates most of the power close to the centre. This means high power densities and Lorentz forces in this region, which, in consequence, limit the performance of the total magnet.

The design of high field magnets is therefore governed by two major concerns:

- the Lorentz forces, which induce hoop stresses easily exceeding the yield stress of the conductor;
- the cooling requirements to evacuate the power dissipated in a region where the stresses are also highest.

2.1. Stresses

The traditional way to build high power, high field laboratory magnets are Bitter magnets [5]. A large number of identical copper discs are piled up and are interleaved with insulators in such a way that a small angular part of the surface remains uncovered and assures contact between the plates. Therefore, the current follows a helical path and a radial current density distribution results which is inversely proportional to the radius. The dissipated power is extracted via a large number (typically 1000) of cooling channels, which are formed by the precisely lined-up cooling holes in each plate and in each insulator. The whole stack is clamped together and gives a single layer solenoid. Strong clamping is required because of the hoop stresses, which have to be transmitted from one disc to the other via friction. Stress calculations adopt with good justifications a model that assumes a homogeneous, isotropic hollow cylinder [6]. Under the influence of the Lorentz forces each volume element of the disc experiences a force in the radial direction which is proportional to the axial component of the magnetic field and the circumferential current density at that point. The outward directed Lorentz forces result in circumferential (or hoop) stresses which attain for this current density distribution ($j \approx 1/r$) the highest value at the inner radius of the coil.

Since the forces change with radius, radial stresses are also set up which are usually directed outward. They pull at the conductor ring and increase further the hoop stress. This stress amplification is a function of the thickness of the coil and depends on the value of the outer background field. It is therefore advantageous to replace a coil by a multitude of concentric coils. A stress reduction of up to a factor of two can be achieved. This also holds to a smaller extent for superconducting coils [4]. It is important to state that this stress reduction is achieved only by introducing mechanical separation in the magnet; neither the magnetic induction nor the radial current density distribution nor the Lorentz forces were changed. By mechanical decoupling, the radial stresses are eliminated and therefore the hoop stresses reduced. However, the displacement of the outer coils increases slightly because they are no longer held by the inner ones and also the highest – although reduced – hoop stress still occurs at the inner radius.

We have therefore proposed to change the radial current density distribution in such a way that each subcoil sees the same hoop stress. As a consequence the voltage drop across the coils will now be different, and so electrical separation of the coils has to be introduced. The word helix is employed for a mechanically isolated thin monolayer coil, which is designed to withstand the electromechanical forces on its own. A polyhelix magnet consists of a set of nested helices, each of them experiencing the same hoop stress.

The radial current density distribution $j(r)$ which gives constant hoop stress can be computed analytically using a simplified model [7] which gives:

$$j(r) = j_0 \left(\frac{a_1}{r} \right) \left[\frac{B_0^2}{\sigma \mu_0 \lambda} + 2 \ln \left(\frac{a_2 (b + \sqrt{r^2 + b^2})}{r (b + \sqrt{a_2^2 + b^2})} \right) \right]^{-1/2}, \quad (1)$$

and for the total magnetic field at the centre, $B_{0,0}$:

$$B_{0,0} = \left[B_0^2 + 2\lambda\mu_0\sigma \ln \left(\frac{a_2(b + \sqrt{a_1^2 + b^2})}{a_1(b + \sqrt{a_2^2 + b^2})} \right) \right]^{1/2}, \quad (2)$$

with

$$j_0 = \sqrt{\frac{\sigma}{\mu_0\lambda a_1^2}}, \quad (3)$$

where a_1 , a_2 , b , λ , σ and B_0 are the inner and outer radii, half length, spacefactor, admissible hoop stress of the magnet and external field, respectively.

The function $j(r)$ depends strongly on the value of the outer field. The higher the outer field, the smaller is the current density in the helices and the bigger is the magnet for the same stress level. As an example, current density distributions for different magnets are shown in fig. 1. In our case the same current passes through each helix, and so the current density is determined by the thickness of each helix. This constant stress current density distribution has the interesting feature that its highest value occurs at the inner radius. It is therefore an efficient distribution. In addition there is an increase of the current density in the outer helices compared to the $1/r$ distribution of a Bitter magnet. It is thus also a more compact distribution. Eq. (2) can be written for big coils as [8]:

$$B \approx \sqrt{\sigma \ln(a_2/a_1)}. \quad (4)$$

The magnetic field that can be generated with polyhelix magnets is obviously only limited by the strength of the conductor material and/or its dimensions.

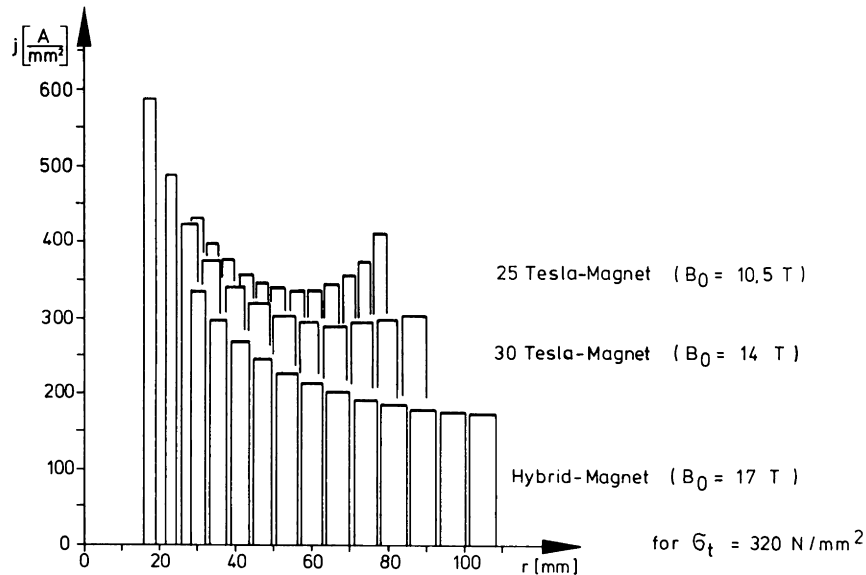


Fig. 1. The current density in polyhelix magnets as a function of the radial position. Each helix experiences the same maximum hoop stress of 320 N/mm^2 .

2.2. Cooling

Bitter magnets have a power density distribution which increases with $1/r^2$ from the outer to the inner radius. The cooling hole pattern follows this law, since usually these magnets are computed for constant heat flux in each cooling hole. This puts most of the holes close to the inner radius. As a result the performance of very high power density magnets is limited because there is simply not enough space for cooling holes.

A solution to this problem are radially cooled Bitter magnets which now have proven to be reliable [9], but they have the inherent disadvantage that a part of the central bore is lost for the supply of the cooling water.

Polyhelix magnets build much smaller than Bitter magnets because of their efficient and more compact current density distribution. At Grenoble a volume reduction of more than a factor of 5 was achieved. This increases, however, the average power density by the same amount. In polyhelix magnets the small annular spaces between the helices, which are needed for the required mechanical and electrical separation, are used for cooling. The total surfaces of both sides of the helices are therefore in direct contact with the coolant. Compared to Bitter magnets, polyhelix magnets offer much larger cooling surfaces. Even for the innermost helix it is higher by at least a factor of 2. Consequently, the high power densities in the conductors (up to 3 MW/litre of coil volume) can be cooled with a modest heat flux of only 5 W/mm^2 .

The distance between the helices is chosen in such a way that the ratio of power/water flow rate is the same in each annulus. As a result, equal water temperatures and practically identical conductor temperatures are obtained. Since the helices are rather short, a high pressure drop (2 bars/cm) results and the roughness of the surface becomes of the same order of magnitude as the distance between the helices. A relation for the friction factor for the kind of roughness used had to be established. From the temperature drop between the coolant and the conductor it was estimated that the laminar layer is only of the order of a few micrometers.

3. Hybrid magnets

It is obvious that with the new technology of polyhelix magnets a continuous field of 25 T in a 50-mm diameter bore seems to represent the upper limit for 10 MW. In principle there are several possibilities to further increase the magnetic field:

- Improving the available conductor materials with respect to strength and conductivity.
- Reducing the bore diameter. This possibility is often applied but reduces the available experimental space, making certain experiments impossible.
- Increasing the power. Fig. 2 shows the basic relationship between the power required and the magnetic field that can be generated. Even for the efficient polyhelix magnets the power requirements soon become excessive. A doubling of the actual field of 25 T to 50 T requires

a 20-fold increase in power and in the cooling infrastructure.

- Surrounding the magnet with a superconducting magnet which provides a booster field. This idea was first proposed in 1966 [10], and it has been pursued by most of the magnet laboratories (table I).

In these hybrid magnets the outer, lower field region is occupied by a superconducting magnet with a large bore generating the background field for the inner resistive magnet.

Although hybrid magnets are rather expensive – the large bore superconducting coil and the cryogenic infrastructure being the most costly part – they are relatively economical as the required additional power supply and the electricity costs for the equivalent resistive magnet would be even more expensive.

The resistive part of a hybrid magnet is exposed to three major constraints: