UvA-DARE (Digital Academic Repository)

Beyond 60 T; a fruitful staircase to long-pulse 100 T fields

Louis, J-M.; Frings, P.H.

Publication date
1995

Published in
Physica B-Condensed Matter

[Link to publication](#)

Citation for published version (APA):

Louis, J-M., & Frings, P. H. (1995). Beyond 60 T; a fruitful staircase to long-pulse 100 T fields. *Physica B-Condensed Matter*, 201, 69-72.

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

ELSEVIER

Physica B 211 (1995) 69–72

PHYSICA B

Beyond 60 T; a fruitful staircase to long-pulse 100 T fields

J.-M. Louis*, P.H. Frings, R. Gersdorf

Van der Waals–Zeeman Laboratory, University of Amsterdam, Valckenierstraat 65, NL-1018 XE Amsterdam, The Netherlands

Abstract

The design study for a power-limited semicontinuous 100 T magnet carried out in Amsterdam is presented. It appears that such a magnet, wound from existing wire material, would become very large and expensive. Several designs are given for smaller magnet coil systems, where the stresses and thermal loads will be the same as in the larger 100 T magnet, producing, for example, 85 T during 1 ms in a 2 cm bore.

1. Introduction

Since 1969 the High Field Facility of the University of Amsterdam has a semicontinuous 40 T, 100 ms coil in operation [1]. The installation will be upgraded in the next few years with a new 60 T, 100 ms coil. Besides that, our Institute is also involved in a European Network for the study of the feasibility of even higher fields in the 100 T region.

The final aim of this study was the design of a magnet capable of producing 100 T during a constant period of the order of 1 s. Preliminary calculations of the heat and stress limited current densities in a more realistic magnet system capable of producing 100 T in an inner bore of 2.5 cm for 100 ms were performed. It turned out that it is possible to build such a magnet with existing materials; however, for the present state of the art in ultrastrong wires technology, a 100 T, 100 ms magnet would require a power of 1 GW and would have a diameter of several meters.

As a pilot study for this 100 T magnet, we restricted ourselves to a scaled down magnet in terms of power, time, size, and energy but kept the same thermal and mechanical loads, resulting in 85 T during 1 ms in an

inner bore of 2 cm. Such a 85 T magnet would require realistic power, energy and dimensions, allowing us to test its detailed behaviour, in connection with novel construction techniques. Furthermore, a small 85 T magnet even with a short constant field plateau gives the possibility for physicists to perform useful measurements once it has been built and tested.

The use of exact scaling laws allows us to scale up this magnet to a 85 T, approximately 50 ms coil with an inner bore of about 15 cm [1]. The next step would then be to design an insert to be placed in this magnet capable of producing 15 T during 50 ms in an inner bore of 2.5 cm. The calculations we have performed showed this to be possible with the same material characteristics.

We have considered different materials either available today, or in the next future. The first category is given by the homogeneous wires, such as copper–beryllium (CuBe) or copper–silver (CuAg), which have a large yield strength and a rather large electrical conductivity. The second category is given by the so-called “composite” wires, which consist of pure copper with a large electrical conductivity reinforced by stainless steel with very large yield strength. The main electrical and mechanical properties of the wires are summarised in Table 1.

For the composite wires, two different situations can be considered, namely *adiabatic* or *isothermal*. In the adiabatic situation the heat created by the current flow in

*Corresponding author.

Table 1
Relevant physical properties of wire materials

	Yield strength (MPa)	ρ^{-1} @RT (%IACS)	ρ_0 ($\mu\Omega$ cm)
CuBe	1400	~ 20	~ 6.0
CuAg	910	83	0.353
Hardened Cu	360	100	0.06
Composite	$\lambda \times \sigma_{Cu}$ + $(1 - \lambda) \times \sigma_{s.s.}$		
Cu (frac. λ)	$\sigma_{Cu} = 100$	100	$\times \lambda$ (%IACS)
Steel (frac. $1 - \lambda$)	$\sigma_{s.s.} = 2000$	See Ref. [2]	

the copper remains there. Larger current densities can be used in the isothermal case, where the heat is, during the pulse, redistributed among the copper and the stainless steel [2].

2. The scaled down magnet

In the following we will consider the design of the 85 T, 1 ms, magnet with an inner bore of 2 cm. The magnet will consist of three sections of concentric coils. Two different, extreme situations can be considered if the total coil system is energised from a power limited supply.

In the innermost coils, where the needed power is almost negligible, the important point is to reduce the outer diameter, so that the power in the outer coils will be strongly reduced by the decrease of the overall radius of the outer system. This imposes the use of very strong wire, which makes the use of high current densities possible. The opposite situation is obtained for the outermost part. There we are clearly in the power limited case. The strength of the wire is not so important. As far as the total pulse time and the demanded power in the outer system are concerned the use of a wire with an electrical resistivity as low as possible has to be considered.

In the intermediate part, we have to find a delicate balance between strong material (reduction of the size) and better conducting material (minimisation of the power). The calculations are based on the formulae describing the mechanical behaviour of coils [1] and optimisation of the magnets is based on paper [3].

2.1. Stress and heat limitations

The two important limitations for the calculation of the allowable current densities in the coils are the *heat* and *stress* limitations. The heat limited current density j_{heat} can be approximated from the resistive and thermal

Fig. 1. Stress and heat limited current densities throughout the 85 T coil. The rectangles represent the division of the coil in subcoils with adapted current densities.

properties of the wire using Eq. (1), where ΔT is the maximum allowable temperature rise, e.g. 250 K. $C_{v,av}$ is the averaged specific heat of the wire, ρ_v is its averaged resistivity, and Δt_c is the duration of the constant field [3]:

$$j_{\text{heat}} \leq \sqrt{\frac{C_{v,av} \Delta T}{\rho_{av} \Delta t_c}}. \quad (1)$$

The stress limited current density j_{stress} is roughly given by Eq. (2), where $B_z(r)$ is the axial field throughout the coil [3]:

$$j_{\text{stress}} \leq \frac{\sigma_c}{1.16rB_z(r)}. \quad (2)$$

Assuming these two equations, we have plotted in Fig. 1 the heat and stress limited current densities for a 85 T, 1 ms coil. We used the mechanical and electrical properties of the CuBe alloy. It turns out that the inner coils are stress limited rather than heat limited; this is due to the short pulse duration. An ideal optimisation would be to adapt continuously the current density and the strength throughout the coil. Since we cannot do this, we have divided the magnet in different parts where the current density is kept constant. This division in subcoils shown in Fig. 1 will be used later on.

The energising of the magnet system is done by a varying number of rectifiers with different voltage and current capacities. Coils #0 to #4 are energised via rectifier #1, coils #5 and #6 by rectifier #2, and coils #7 and #8 by rectifier #3. The initial temperature is always liquid nitrogen temperature.

2.2. Design using homogeneous wires

In the inner part of a 85 T magnet system where the highest stresses exist, a very strong wire material is used. Our first choice was the copper beryllium. The resulting inner part is capable of producing an additional field of about 55 T at a background field of 30 T, with an outer radius of 23.5 cm.

The background field is produced in an outer part of the system wound of CuAg, which allows to gain on the power, where the strength of the wire is less important. The overall radius of this magnet system is around 48 cm. The total power we calculated for this entire system is about 525 MW, the total pulse time is about 2.8 s and the stored energy 210 MJ.

2.3. Design using composite wires

In this part, a design for the 85 T magnet, using realistic or existing material is given. We present first the results we got for the almost realistic situation of an “adiabatic” wire formed of a copper wire externally reinforced with stainless steel.

The final inner part is capable of producing 55 T in an inner bore of 2 cm for 1 ms. The total power needed by this system is around 125 MW and the outer radius is 23.5 cm. The inner coils have been designed in order to be heat and stress limited everywhere. This subsystem requires an outer part producing 30 T.

The outer part can be designed using composite wire with a lower fraction of stainless steel, since the stresses are lower. The stainless steel fractions have been recalculated afterwards to match the stresses. This design requires the least power among all. The total power is about 290 MW, the total pulse time is 4.2 s, and the total stored energy is around 180 MJ. Since the power is the more expensive part of such a project, this design has been power optimised. Fig. 2 shows the typical field profile of the 85 T pulse.

The first two designs concerned existing materials. We will now consider the case of “isothermal” composite wires to show that further developments in ultrastrong conducting wires technology are of great importance. This aspect is developed in the related paper “strength versus conductivity” [2].

2.4. “Isothermal” composite wire

We have calculated a magnet capable of producing 85 T for 1 ms using a hypothetical “isothermal” composite material. Experiments performed on this new material may be successful in the next future and provide us with a very strong and conducting wire. We have con-

Fig. 2. Field profile of the “adiabatic” composite coil.

sidered a wire where it is possible to adapt the relative fractions of materials, and performed the calculations in both power and size minimised ways, since these are the two different ways of optimising magnets. One can try to decrease the total needed power or the overall radius of the magnet using higher current densities. The actual volume would become lower than the optimum volume (giving the lowest power) and the needed power would strongly increase.

The size optimised design is an extreme case where the dimensions of the system are as small as possible, in order to show that we can design very compact magnet systems with this wire technology. The power and energy for this system are 400 MW and 34 MJ, respectively.

The opposite extreme situation can also be reached, where we concentrate more on the minimisation of the power, and less on the magnet size. We have designed a 85 T coil on the basis of a power of the order of 150 MW. The size and pulse duration of such a low power magnet is increased compared to the previous one.

3. A 100 T system

Finally, as an example for a complete 100 T system, we present the results of calculations we have performed on a scaled-up 85 T magnet provided with an insert creating the additional 15 T (see Table 2). The starting 85 T magnet was the so-called “size minimised isothermal composite” magnet since its dimensions are relatively small.

Table 2

Summary of the important features for the considered 85 T, 1 ms and 100 T, 60 ms magnets (see text)

Design	Outer radius (cm)	Power # 1, Field	Power # 2, Field	Power # 3, Field	Total power (MW)	Energy (MJ)	Pulse duration (s)
CuBe/CuAg	48	129 MW, 30 T	214 MW, 27 T	182 MW, 28 T	525	208	2.9
Adiabatic composite	55	70 MW, 33 T	57 MW, 23 T	161 MW, 29 T	290	180	4.2
Isothermal composite power minimised	47.3	52 MW, 35 T	66 MW, 32 T	31 MW, 18 T	150	100	7.0
Isothermal composite size minimised	20	115 MW, 38 T	281 MW, 47 T	—	396	34	0.32
100 T (large power)	100	14 MW, 15 T	567 MW, 38 T	1343 MW, 47 T	1925	2500	8.0
100 T (low power)	236.5	18 MW, 15 T	302 MW, 35 T	239 + 179 MW, 32 + 18 T	738	6390	170

We used a scaling factor of 5, giving a total power of around 2000 MW, and a total pulse duration of about 8 s for an outer diameter of 2 m. If we start from the “power minimised” magnet, the resulting system is somewhat larger (5 m in diameter) and has a strongly reduced power of about 0.75 GW, the total pulse duration is, however, dramatically increased.

References

- [1] R. Gersdorf, F.A. Muller and L.W. Roeland, *Rev. Sci. Instrum.* 36 (1965) 1100.
- [2] P.H. Frings and L. van Bockstal, *Physica B* 211 (1995) 73.
- [3] R. Gersdorf and P.H. Frings, Optimisation of coils for semi-continuous magnetic fields, *Physica B*, to be published.