CERN 89-04
10 March 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CAS CERN ACCELERATOR SCHOOL
SUPERCONDUCTIVITY IN PARTICLE ACCELERATORS

Haus Rissen, Hamburg, Fed. Rep. Germany
30 May - 3 June 1988

PROCEEDINGS
Editor: S. Turner

GENEVA
1989

© Copyright CERN, Genève, 1989

Propriété littéraire et scientifique réservée pour tous les pays du monde. Ce document ne peut être reproduit ou traduit en tout ou en partie sans l'autorisation écrite du Directeur général du CERN, titulaire du droit d'auteur. Dans les cas appropriés, et s'il s'agit d'utiliser le document à des fins non commerciales, cette autorisation sera volontiers accordée.

Le CERN ne revendique pas la propriété des inventions brevetables et dessins ou modèles susceptibles de dépôt qui pourraient être décrits dans le présent document; ceux-ci peuvent être librement utilisés par les instituts de recherche, les industriels et autres intéressés. Cependant, le CERN se réserve le droit de s'opposer à toute revendication qu'un usager pourrait faire de la propriété scientifique ou industrielle de toute invention et tout dessin ou modèle décrits dans le présent document.

Literary and scientific copyrights reserved in all countries of the world. This report, or any part of it, may not be reprinted or translated without written permission of the copyright holder, the Director-General of CERN. However, permission will be freely granted for appropriate non-commercial use.

If any patentable invention or registrable design is described in the report, CERN makes no claim to property rights in it but offers it for the free use of research institutions, manufacturers and others. CERN, however, may oppose any attempt by a user to claim any proprietary or patent rights in such inventions or designs as may be described in the present document.

ISSN 0007-8328
ISBN 92-9083-009-3

CERN 89-04
10 March 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CAS CERN ACCELERATOR SCHOOL
SUPERCONDUCTIVITY IN PARTICLE ACCELERATORS

Haus Rissen, Hamburg, Fed. Rep. Germany
30 May - 3 June 1988

PROCEEDINGS
Editor: S. Turner

GENEVA
1989

CERN — Service d'Information scientifique — RD/775 - 3500 - Mars 1989

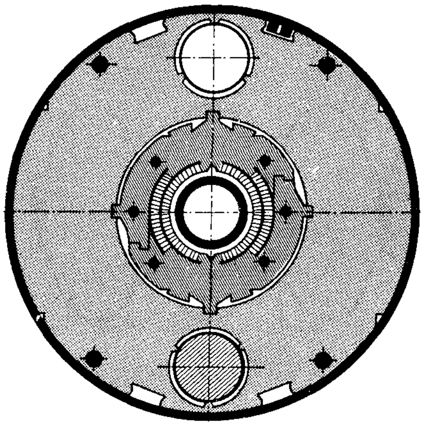
ABSTRACT

One of the objectives of the CERN Accelerator School is to run courses on specialised topics in the particle accelerator field. The present volume contains the proceedings of one such course, this time organized in conjunction with the Deutsches Elektronen Synchrotron (DESY) on the subject of superconductivity in particle accelerators. This course reflects the very considerable progress made over the last few years in the use of the technology for the magnet and radio-frequency systems of many large and small accelerators already in use or nearing completion, while also taking account of the development work now going on for future machines. The lectures cover the theory of superconductivity, cryogenics and accelerator magnets and cavities, while the seminars include superfluidity, superconductors, special magnets and the prospects for high-temperature superconductors.

CERN ACCELERATOR SCHOOL
&
DEUTSCHES ELEKTRONEN SYNCHROTRON - DESY

will jointly organize a course on

SUPERCONDUCTIVITY IN PARTICLE ACCELERATORS



30 May - 3 June 1988
at Haus Rissen, Hamburg

Lectures:
- Superconductivity
- Cryogenics
- SC magnets and cavities
- SC quantum effects
- Survey of high-temperature superconductors (HTSC)
- Thin-film production for HTSC
- Potentials and limitations of HTSC for high fields

Seminars:
- Superfluidity
- Practical conductors
- Special magnets
- Application prospects for HTSC

Visit:
DESY-HERA

General information Persons wishing to attend this course can obtain further information and application forms from the CERN Accelerator School, Mrs. S. von Wartburg, LEP Division, CH-1211 Geneva 23, or by electronic mail CASDESY @ CERNVM. Application forms must be returned by 14 MARCH 1988. The registration fee is SFR 600 per person for a single room and includes full board. For rates for double rooms, local students and for non-participating accompanying persons (space permitting) please see registration form. All participants will receive a copy of the proceedings of the course. The number of participants is limited to 100.

Administration *Head of School:* P.J. Bryant; *Programme Committee:* P.J. Bryant, C. Daum, E. Haebel, R. Perin, J. Perot, H. Piel, D. Proch, P. Schmüser, S. Tazzari, B. Wiik; *Local Organizing Committee:* P.J. Bryant, P. von Handel, I. Schwartz, S. Turner, S. von Wartburg.

Sponsored by: BBC BROWN BOVERI and DORNIER

BBC Brown Boveri AG
Physikalische Anlagen
6800 Mannheim 1

JOINT CAS-DESY COURSE ON SUPERCONDUCTIVITY IN PARTICLE ACCELERATORS, HAMBURG 1988

	Monday 30th May	Tuesday 31st May	Wednesday 1st June	Thursday 2nd June	Friday 3rd June
09.00 09.15	Welcome -------------------- Superconductivity I W. Buckel	Superconductivity III W. Buckel	S.C. Magnets II P. Schmüser	S.C. Magnets III P. Schmüser	General Survey of High-Temperature Superconductors (HTSC) Ø. Fischer
10.00	C O F F E E				
10.20	Cryogenics I J.L. Olsen	Cryogenics III Ph. Lebrun	Cryogenics IV Ph. Lebrun	S.C. Cavities III H. Lengeler	Thin Film Production & Properties of HTSC M. Karkut
11.20	B R E A K				
11.30	Superconductivity II W. Buckel	S.C. Magnets I P. Schmüser	S.C. Cavities II H. Piel	S.C. Magnets IV K. Mess	S.C. Quantum Effects R. Vaglio
12.30	L U N C H				
14.00	Cryogenics II J.L. Olsen	S.C. Cavities I H. Piel	VISIT TO DESY AND BUFFET	S.C. Cavities IV H. Lengeler	Potentials and Limitations of HTSC Wires R. Flükiger
15.00	T E A			T E A	
15.30	Seminar and Film Superfluidity P. Seyfert	Seminar Practical conductors H.H.J. ten Kate		Seminar Special Magnets J. Perot	Seminar Application Prospects for HTSC P. Komarek
17.00	COCKTAIL			B A N Q U E T	
18.30	D I N N E R				

FOREWORD

The proceedings presented in this volume result from an intensive course on superconductivity held in Hamburg, 30 May - 3 June, 1988. This course was jointly organised by the Deutsches Elektronen Synchrotron (DESY), who are presently constructing Europe's largest superconducting accelerator, and the CERN Accelerator School (CAS) who, in addition to a regular programme of general and advanced accelerator physics courses, also arrange specialised and topical courses such as the present one.

The importance of superconductivity to accelerators has been steadily increasing as both large and small machines take advantage of this technology. The largest existing proton accelerator and the future projects for this class of machine all exploit superconducting magnets. It is sure that future large electron machines will rely on superconducting radiofrequency systems and it is likely that superconducting compact synchrotron light sources and cyclotrons will become commonplace facilities in the world's laboratories, universities, hospitals and factories.

The growth of superconductivity in the accelerator field is not isolated. Indeed it is matched by an equally, if not more, spectacular interest outside. Possible applications range from heavy electrical engineering, such as magnetically levitated vehicles, to the microelectronics in computers. The recent discovery of warm superconductors has added a further dimension to this interest, which promises a wealth of new (and as yet unrealised) applications, rather than a revolution in the present uses of classical superconductors. We are therefore fortunate in being part of an extremely exciting development.

Organisation of this superconducting school and the publication of its proceedings is the result of the generous support of very many people. We particularly thank the DESY and CERN Directorates for their help and encouragement, the CAS Advisory Committee for their constant guidance, and the Programme and Local Organising Committees who did so much to ensure the success of this course. The lecturers also deserve a very special word of thanks for all the work they put into preparing, presenting and writing-up their respective topics. The sponsorship of BBC and Dornier was highly appreciated as was the great effort made by the staff of the Haus Rissen conference centre to ensure that we had a fruitful and enjoyable stay there. Last, but certainly not least, we thank the participants who made the meeting meaningful and so worthwhile.

B. Wiik	University of Hamburg
P.J. Bryant	CAS
S. Turner	Editor

CONTENTS

SUPERCONDUCTIVITY

Werner Buckel

University of Karlsruhe, Karlsruhe, Fed. Rep. Germany

ABSTRACT

Three lectures will be devoted to a basic introduction into the properties of superconductivity. The lectures will be organized as follows:

1.1. A SHORT SURVEY ON THE HISTORY OF SUPERCONDUCTIVITY

1908 Heike Kamerlingh Onnes succeeded to liquify helium (boiling point $T_B = 4.2$ K)
1911 Discovery of superconductivity of Hg by H. K. Onnes and van Holst (transition temperature $T_c = 4.2$ K, nearly at the boiling point of He)
1914 Persistent current experiments, $\rho_s/\rho_n < 10^{-8}$
1933 Meissner-Ochsenfeld effect
1935 Phenomenological theory of Fritz and Heinz London; Superconductivity is recognized as a macroscopic quantum phenomenon
1950 Ginsburg-Landau theory; an improved phenomenological theory
1950 Observation of the isotope effect on Hg-isotopes
1957 Bardeen-Cooper-Schrieffer theory; a successful microscopic theory of superconductivity
1957 First experimental determination of the energy gap
1961 Experimental observation and quantitative determination of the flux quantization
1961 Single electron tunneling between superconductors
1962 Josephson effects
1966 Experimental observation of the flux tube lattice in type 2 superconductors
1974 Nb_3Ge: $T_c = 23.2$ K; highest T_c until 1986
1986 La-Ba-Cu-O system; T_c-values as high as 35 K
1987 $YBa_2Cu_3O_7$; $T_c = 95$ K
1988 $Tl_2Ba_2Ca_2CuO_x$; T_c = ca. 125 K

1.2. SUPERCONDUCTING MATERIALS

In 1908, when H. Kamerlingh Onnes succeeded to liquify helium, he immediately started research in the new temperature range. His first question concerned the electrical resistance of pure metals. After some experiments with Pt and Au samples, he decided to study Hg because this metal could be cleaned very efficiently by distillation. Figure 1 shows the original curve by Onnes and van Holst in 1911.

In the following decades, it could be shown that superconductivity is a quite common phenomenon among pure metals and metallic alloys. In table 1 the pure metals which can become superconducting are listed. Many hundreds of metallic alloys and compounds are superconductors. Until 1986, the superconductors of the type Nb_3Sn, the A15 compounds, were the record holders with regard to T_c (Nb_3Ge: T_c = 23.2 K). Some other interesting materials should be mentioned here. The Chevrel-phases of the type $PbMo_6S_8$ have very high critical fields. We know also organic materials with metallic conductivity which show superconductivity. The transition temperature reaches values up to about 10 K ($(BEDT\text{-}TTF)_2Cu(NCS)_2$: T_c = 10.4 K). However, these organic materials are not the organic superconductors proposed by W. A. Little in 1964.

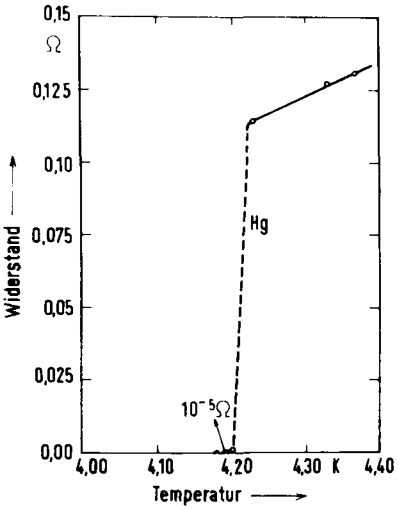


Fig. 1. Transition curve of Hg observed by H. K. Onnes and van Holst

In 1986, K. A. Müller and J. G. Bednorz discovered the superconductivity of the Cu-O-ceramics. They found T_c-values above 30 K for the La-Ba-Cu-O system. This discovery created a tremendous excitement among the physicists. A few months after the discovery of Müller and Bednorz, C. W. Chu found in the system Y-Ba-Cu-O transition temperatures around 90 K, this means above the boiling point of liquid N_2. Special lectures are devoted to these exciting materials.

Table 1

Superconducting elements, T_c in K

element	T_c	element	T_c	element	T_c	element	T_c	element	T_c
Al	1.19	Mo	0.92	Ru	0.5	W	0.01	Cs	1.5
Be	0.03	Nb	9.2	Sn	3.72	Zn	0.9	Ge	5.4
Cd	0.55	Np	0.07	Ta	4.39	Zr	0.55	Lu	0.1-0.7
Ga	1.09	Os	0.65	Tc	7.8	only in pressure phases		P	4.6-6.1
Hf	0.13	Pa	1.3	Th	1.37			Sb	3.6
Hg	4.15	Pb	7.2	Ti	0.39	As	0.5	Se	6.9
In	3.40	Re	1.7	Tl	2.39	Ba	5.1	Si	6.7
Ir	0.14	Rh	3.2×10^{-4}	U(α)	0.2	Bi	3.9-8.5	Te	4.5
La	4.8			V	5.3	Ce	1.7	Y	1.5-2.7

1.3. THE ELECTRICAL RESISTANCE

After the discovery of superconductivity on Hg (Fig. 1), immediately the question arose how large the resistance drop really is, in other words, which upper limit of the eventually still existing resistance can be given. Already Onnes and his c -workers performed the ultimate experiment. They produced an electrical current within a superconducting ring and studied the time dependence of this current (Fig. 2).

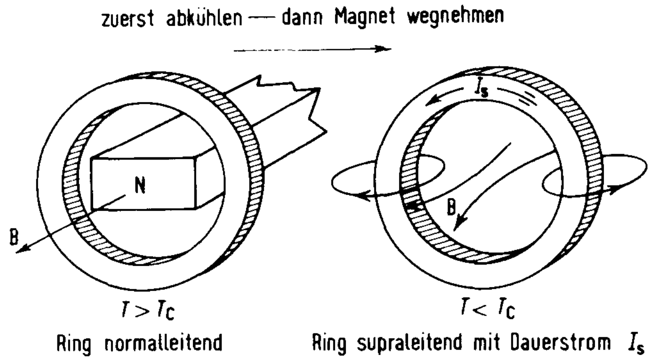


Fig. 2. Persistent current in a superconducting ring

Even very small resistances can be detected in this way by the decay of the current. No decay could be observed. From this result they could conclude that the resistivity ρ_s in the superconducting state is at least 10^8 times smaller than the resistivity ρ_n in the normal-conducting state, $\rho_s/\rho_n < 10^{-8}$. From improved experiments we know today that this ratio is smaller than 10^{-12}.

It has to be kept in mind that this statement only holds for direct currents. With regard to alternating currents, in principle, an electric resistivity exists even in the superconducting state. Alternating currents create electric fields in the sample. These fields accelerate the normal electrons which can dissipate energy. These effects become important for high-frequency currents, e.g. in superconducting cavities.

Summarizing all our experience we can state that the DC resistivity of the superconducting state can be taken as zero for all practical purposes. It is certainly allowed to use the equation

$$R_{DC} = 0 \tag{1}$$

for the superconducting state of macroscopic superconductors.

1.4. THE MEISSNER-OCHSENFELD EFFECT

In 1933 W. Meissner and R. Ochsenfeld made a very important discovery. They found that the superconductor excludes a not too large magnetic induction B from its interior. Figure 3 describes the effect schematically. As the magnetic susceptibility μ is small for non-ferromagnetic metals, the magnetic induction penetrates into the material at $T > T_c$. In the superconducting state, $T < T_c$, the magnetic induction is excluded. Figure 4 shows the Meissner-Ochsenfeld effect for a spherical sample. As the demagnetization factor of a sphere is 1/3, the magnetic field at the equator amounts to 3/2 of the magnetic induction B_a applied to the sample.

The Meissner-Ochsenfeld effect is a completely new and very characteristic property of the superconducting state. It cannot be deduced only from the knowledge $R_{DC} = 0$. The discovey of the Meissner-Ochsenfeld effect was very important for the thermodynamic description of the superconducting state because

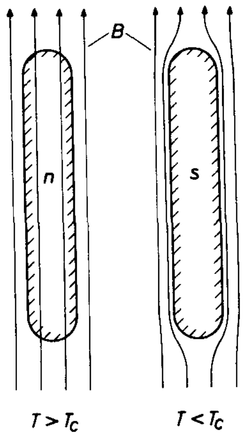


Fig. 3. Meissner-Ochsenfeld effect of a superconductor with a demagnetization factor n nearly zero

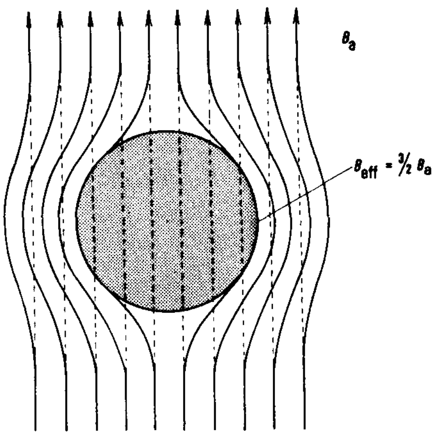


Fig. 4. Meissner-Ochsenfeld effect of a superconducting sphere (n = 1/3)

the field exclusion is a necessary condition for treating the superconducting state as a new thermodynamic phase. We will come back to this point later.

The field exclusion is produced by superconducting surface currents. "Surface currents" means that the screening currents are flowing within a very thin surface layer of the average thickness λ. λ is called the "penetration depth". For classical superconductors, like Hg, In, Tl and others, λ amounts to several tens of nm. It depends on the density of the superconducting electric charge (sloppily expressed "the density of superconducting electrons"). λ is proportional to $1/\sqrt{n_s}$ (n_s = density of superconducting electrons).

1.5. THE SPECIFIC HEAT

Already in the beginning of the thirties it has been observed that the specific heat undergoes a crucial change at the transition temperature. Figure 5 shows the specific heat c_p of Sn in the temperature range below 4 K. At 3.7 K, the transition temperature of Sn, c_p (open circles) exhibits a finite jump. In the superconducting state c_{ps} drops faster than the specific heat of the normal state c_{pn} (full circles) measured in a magnetic field which destroys superconductivity. c_{ps} becomes even smaller than c_{pn} at low temperatures. This behaviour clearly shows that the entropy of the superconducting state is smaller than that of the normal state. This result was very important because it showed that the transition into the superconducting state is connected with some ordering processes in the electron system. The microscopic theory of Bardeen, Cooper and Schrieffer showed that in the superconducting state the electrons are paired, and these pairs are condensed into the ground state of the system.

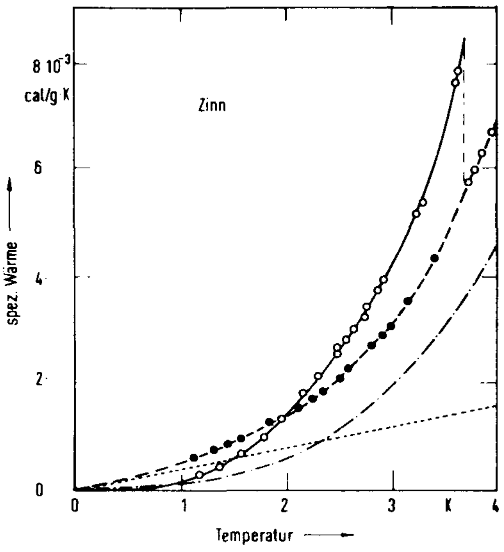


Fig. 5. Specific heat of Sn in the superconducting (open circles) and the normal (full circles) state.
.... contribution of the electrons
-.-.-.- contribution of the lattice

2.1. THE THERMODYNAMICS OF THE SUPERCONDUCTING STATE

With the discovery of the Meissner-Ochsenfeld effect it has been verified that the superconducting state corresponds to a new thermodynamic phase. We will here briefly discuss the thermodynamic of the superconducting state.

2.1.1. The critical magnetic induction

As any thermodynamic phase, the superconducting state is only stable within special ranges of relevant variables. For the superconducting state such variables (among others) are mainly the temperature T and the magnetic induction B. Soon after the discovery of superconductivity, H. K. Onnes and his co-workers found that the superconducting state can be destroyed by a magnetic field. If an external magnetic field of induction B exceeds a critical value B_c, the sample becomes normal-conducting. The phase diagram demonstrating this behaviour is shown in Fig. 6. Only in the area below the critical induction curve $B_c(T)$ the superconducting state is stable.

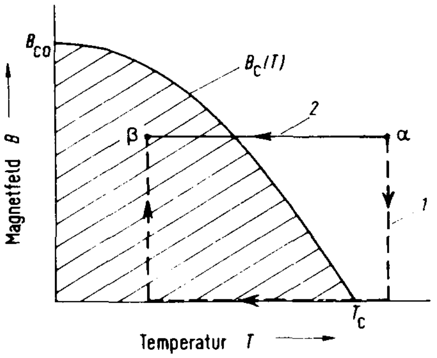


Fig. 6. Phase diagram of a superconductor

Now, we can see why only the Meissner-Ochsenfeld effect gave us the possibility to call the superconducting state a thermodynamic phase. We consider the two ways 1 and 2 from point α to point β in the phase diagram. Using way 1 we cross the phase boundary at the magnetic induction B = 0 and increase the induction to B_β while the sample is superconducting. The change of the induction dB/dt induces persistent currents which screen the interior of the sample from the external induction B_a. At point β we come to a state with no magnetic induction inside the sample. On way 2, on the other hand, we cross the phase boundary at the finite and constant induction B. No electromagnetic induction due to dB/dt can create persistent currents.

If we would only know R = 0, we would expect that the magnetic induction B remains within the sample. We would come to different states using way 1 or way 2. If this would be true, the superconducting state could *not* be called a *thermodynamic phase. The field exclusion is crucial for the thermodynamic.*

The existence of a critical magnetic induction is crucial for almost all applications of superconductivity. The classical superconductors have rather low critical fields. These small critical inductions of the superconductors known by H. K. Onnes were the reason why Onnes could not realize his idea to built a superconducting magnet at that time. Almost 50 years of intensive research were necessary to understand how one can overcome this limitation by using superconductors of type 2.

Figure 7 shows the temperature dependence of the critical induction for some classical superconductors. A rather good approximation for the $B_c(T)$ is given by the following formula:

$$B_c(T) = B_c(0) \cdot (1 - (T/T_c)^2) \qquad (2)$$

Using this approximation one can derive almost all thermodynamic quantities as the entropy, the specific heat and others.

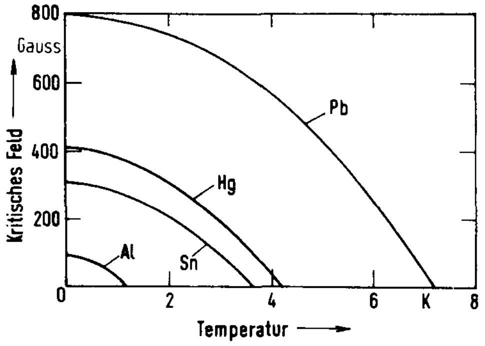


Fig. 7. Critical inductions $B_c(T)$ of some superconductors

2.1.2. The critical current density

A superconducting wire can carry only superconducting currents up to a critical current I_{cs}. If one exceeds this critical current I_{cs}, the wire becomes normal-conducting. As the interior of the wire in the superconducting state has to be free of magnetic induction, the current can only flow within a thin surface layer of the thickness λ. Due to the inhomogeneous distribution of the current, it is better to consider the current density j_{cs}. The existence of a critical current density j_{cs} follows immediately from the existence of a critical magnetic induction B_c.

A current through a wire with circular cross section (radius r) produces a magnetic induction at the surface $B(r) = \mu_0 I/2\pi r$. If this induction exceeds the critical value B_c, the superconducting state is destroyed (F. B. Silsbee 1916). This simple relationship holds only for samples which are thick enough to screen the magnetic induction completely. It has to be varied if the sample becomes comparable with the penetration depth, e.g. for thin films with thickness smaller than λ.

From the phase diagram (Fig. 6) we can determine the transformation energy connected with the transition from the normal- to the superconducting state. When we increase the external magnetic induction screening, currents are created. This means that the Gibbs function G_s of the superconducting state increases. At B_c, G_s reaches the value of the Gibbs function of the normal state G_n.

$$G_n - G_s = \frac{V_s}{\mu_0} \int_0^{B_c} B \, dB = V_s \frac{B_c^2}{2\mu_0} \tag{3}$$

(V_s = volume of the superconductor, $\mu_0 = 2\pi \cdot 10^{-7}$ Vs/Am)

2.2. TYPE 1 AND TYPE 2 SUPERCONDUCTORS

At the end of the thirties experiments with alloys showed that alloys normally have much larger critical magnetic inductions than pure elements. Ginsburg and Landau formulated a phenomenological theory which could explain these observations. One learned that under special conditions the magnetic induction B can penetrate into the superconductor at B-values much smaller than B_c. The B value at which the induction starts to penetrate is called B_{c1}, the "lower critical induction". If the magnetic induction can penetrate into the superconductor, the screening currents remain smaller than in the case of complete screening. This means that the external induction B has to be increased to larger values to increase the Gibbs function G_s to G_n. The induction at which $G_s(B)$ becomes equal to G_n is called B_{c2}, the "upper critical induction".

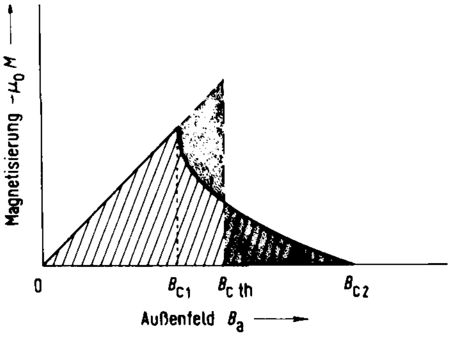


Fig. 8. Magnetization of type 1 and type 2 superconductors with a demagnetization factor 0

Figure 8 demonstrates the difference between type 1 and type 2 superconductors. The negative magnetization $\mu_0 M$ (the superconductor behaves as a diamagnet) is plotted versus the external induction B_a. The type 1 superconductor excludes the external induction until B_c is reached. At $B_a > B_c$ the superconductivity is destroyed. For type 2 superconductors the induction penetrates into the sample at $B_{cl} < B_c$. The superconductivity is completely destroyed only at $B_{c2} > B_c$.

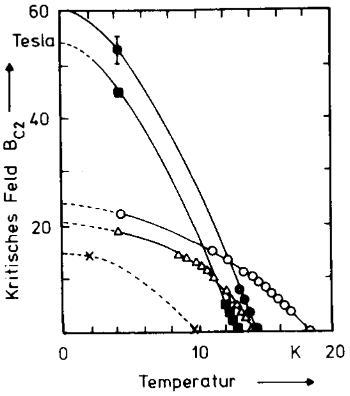


Fig. 9. B_{c2} values for some type 2 superconductors; o-o Nb_3Sn, -△-△- V_3Ga, x-x- $Nb_{50}Ti_{50}$, -■-■- $PbMo_6S_8$, -●-●- $PbGd_{0.3}Mo_6S_8$

Figure 9 shows the B_{c2} values of some type 2 superconductors. With these material one could again try to build superconducting magnets. However, it turned out that a further condition has to be fulfilled to make a superconducting wire suitable for a superconducting magnet. One has to introduce so-called "pinning centers" into the superconductor. Only superconductors of type 2 with pinning centers can carry large electric currents in large external magnetic inductions B_a.

To understand the necessity of pinning centers one has to consider how the magnetic flux penetrates through the superconductor for inductions B_a with $B_{cl} < B_a < B_{c2}$. Using the Ginsburg-Landau theory, A. A. Abrikosov showed that the magnetic flux Φ is concentrated in so-called "flux tubes". In an ideally homogeneous superconductor of type 2 these flux tubes, each carrying one flux quantum, are arranged in a regular lattice.

Figure 10 schematically shows the distribution of the magnetic flux of such a flux tube lattice. The flux tubes can be decorated at the surface by very small iron particles.

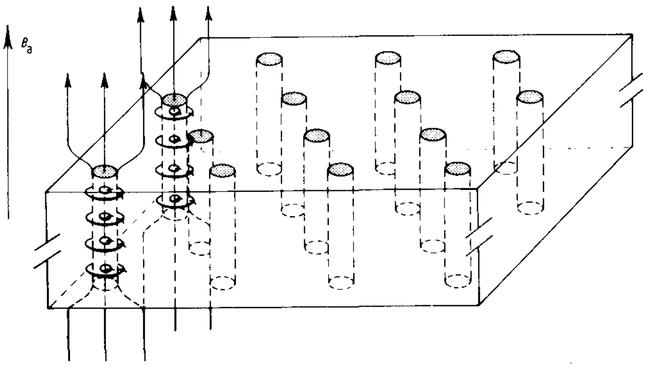


Fig. 10. Schematic drawing of a flux tube lattice

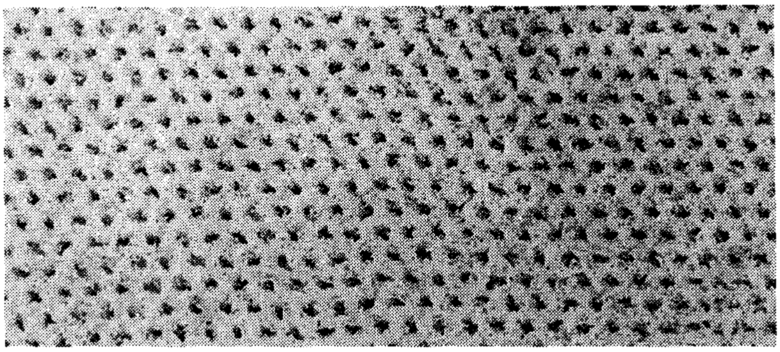


Fig. 11. Electron microscope picture of an iron decorated flux tube lattice at the surface of a Pb-In alloy

The existence of the flux tube lattice has been confirmed by such decoration experiments. Figure 11 shows the electron microscope picture of such a decorated flux tube lattice after U. Eßmann und H. Träuble.

At this occasion we will briefly discuss the flux quantization in a superconducting ring. F. London has pointed out already in the thirties that the magnetic flux Φ (more correct the "fluxoid") through a superconducting ring should be quantized in integer numbers of Φ_{0L}. F. London assumed electrons with the electric charge e as the particles which carry the superconducting current. From this he predicted $\Phi_{0L} = h/e = 4 \cdot 10^{-7}$ Gauss.cm^2 = $4 \cdot 10^{-15}$ Volts. 1961 two groups, R. Doll and M. Näbauer at Munich, and B. S. Deaver Jr. and W. M. Fairbank at Stanford, confirmed the flux quantization and determined $\Phi_{0L} = 2 \cdot 10^{-7}$ Gauss.cm^2. These experiments were an exciting confirmation of the microscopic theory of J. Bardeen, L. N. Cooper and J. R. Schrieffer. These authors predicted in their theory that electron pairs, the Cooper pairs, should carry the superconducting current. Therefore, the new particles are electron pairs with charge 2e, and the flux quantum becomes $\Phi_0 = h/2e = 2 \cdot 10^{-7}$ Gauss. cm^2.

We come back to our consideration of the type 2 superconductors in a magnetic field. If such a superconductor with a flux tube lattice (Fig. 10) is carrying a current perpendicular to the flux tubes, the Lorentz force acts on the flux tubes. In an ideally homogeneous superconductor no preferred sites exist for the flux tubes. The Lorentz force will move the flux tubes. The movement of a magnetic flux causes electric fields by induction and in this way dissipative processes which means resistance. To fix the flux tubes one has to introduce pinning centers for the flux tubes. Such pinning centers are small normal-conducting particles, dislocation configurations or grain boundaries. Such type 2 superconductors with pinning centers are called "hard superconductors". Only such hard superconductors can be used for the construction of superconducting magnets.

It was a long way - almost 50 years of intensive research - from the first effort of H. K. Onnes to the succesful construction of a superconducting magnet. Today, we have superconducting wires which have critical current densities of several 10^5 A/cm^2 in magnetic inductions up to 15 Tesla.

2.3. THE TUNNEL EFFECTS

The tunneling of electrons and electron pairs through a potential barrier between superconductors was developed early in the sixties as a very powerful tool to study superconductivity.