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5 cm, 17 cm and 35 cm in Diameter.

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The contents of this report will be presented at the Fifth Symposium on Fusion Technology, Oxford, England 2nd - 5th July 1968.

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Institut für Plasmaphysik GmbH und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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A System of Superconducting Coils 5 cm, 17 cm and 35 cm in Diameter.

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Abstract

In order to prove the feasibility of large superconducting coils in plasma physics, a number of module-type standard coils were developed and tested. Various numbers of three different coil types can be combined to form variable field geometries. The maximum field provided would be about 100 KG.

The test results are compared with the short sample characteristic of the different superconducting materials, such as Nb_3Su tape and NbTi composite cable.

The application of superconducting coils could be of economical advantage for many experiments in plasma physics. A comparison of conventional water-cooled coil systems for fields up to 70 KG with superconducting coils shows that superconducting systems become competitive, if fields have to be maintained for more than a few seconds.

This results from a calculation of some optimized cylindrical field configurations 10 to 20 cm in inner diameter, if the power supplies, cooling devices and power costs are taken into account in addition to the coils.

Such a calculation may easily be based on specific data of commercial superconductors, such as costs per current and length, stable current density etc. However, even in the present state of superconducting magnet technology there is still a small degree of impredictability and the step from theory to practice may produce surprises.

In order to prove the feasibility of superconducting coils for plasma physics and at the same time to perform preliminary work for a large superconducting mirror field system, a number of relatively large coils and some additional components, such as current leads, contacts etc., were developed and tested.

1. Coil design and construction

In view of the various requirements in plasma physics the development of a number of standard coil types for use in different combinations seemed to be of fundamental importance. Therefore three different modul-type coils were designed and constructed. They can be piled up to form various cylindrical configurations capable of producing homogeneous fields of different lengths and intensities with radial access, or mirror fields or cusp fields etc. Furthermore their construction should enable us to test different superconducting materi-als over a wide field range up to 100 KG.

The coil dimensions are listed in Table I.

Type	D_i	D_a	L	Number of turns	Deliv. from	Material Dimension	Short curr.	sample field
	cm	cm	cm			mm	A	kG
SSP 50 a,b,c,	5	17	8	1480	GE	0.1x12.5 Nb_3Sn	300	100
d,	5	17	8	1200	RCA	0.12x12.5 Nb_3Sn	600	100
SSP 170 a,b,c,d,	17	35	8	395	SUPERCON	6x0.024" inner sect.	1230	50
						4x0.024" outer sect. NbTi	820	50
SSP 350 a,b,	35	53	8	595	SUPERCON	6x0.018" inner sect.	780	50
						4x0.018" outer sect. NbTi	520	50
SSP 350 c.d,	35	53	8	575	At.Int.	6x0.8 mm inner sect.	800	50
						3x0.9 mm outer sect. NbTi	520	50

Table I Coil Dimensions

Four coils of each type were built by using superconductors supplied by various manufacturers. They can be operated independently or in combination. Various numbers of each coil type can also be combined concentrically. A compact combination of all of these would afford a coil system with an axial length of 32 cm and an inner diameter of 5 cm. The expected maximum field in this case would be about 100 KG.

This coil combination is shown schematically in Fig. 2. One can see from Table I that each coil of the types SSp 170 and SSp 350 consists of two winding sections. The maximum local field of each section corresponds to approximately the same critical current. In other words, the coils are optimized in two radial steps.

The Supercon cables used for the inner sections contain 6 superconducting strands, while the corresponding outer sections have 4 of same size.

All cables used are indium - impregnated. Their cross section is shown in Fig. 1.

At the present stage in the development of superconducting materials cables like these are being gradually superseded by rectangular composite multistrand conductors. However, indium represents a medium of high heat capacity at low temperature and therefore gives the cables more than twice the average heat capacity compared with corresponding copper conductors.

Since the coils are not fully stabilized-current densities between 120 and 200 A/mm^2 could be achieved - the heat capacity of the conductor is still of some importance. The cables are insulated with Mylar tape which covers the whole surface.

Two cable lengths for the inner and the outer winding sections, e. g. A and B in the case of SSp 170, are connected by overlapping and soldering the ends over a length of about 20 cm after the outer copperstrands have been removed.

The measured joint resistance is about 10^{-9} Ohms. The joints are brought to the outside of the coil windings. There they are exposed to liquid helium along the entire length.

The winding layers are insulated from each other by perforated glass fibre interlayers, thus allowing the helium to penetrate the whole winding volume.

At the ends of the windings the single superconducting strands are soldered seperately to plane contact plates mounted on the outer circumference of the coil former.

Two coils are connected in series by Nb_3Sn-strips supported or stabilized by copper sheets. They are indium soldered to the contact plates and can be easily removed.

The connection resistances are measured to be lower than 10^{-8} Ohms. The maximum heat flow to the surrounding liquid helium is lower than 10^{-4} W/cm^2 and therefore well below a critical value. Actually, even at the highest currents no negative influence on the behaviour of the coils due to these contacts could be observed.

The cable dimensions and compos-itions provided for the coils SSp 170 and SSp 350 are designed to allow series connection of all coils, if they are operated in concentric combination. In this case, the critical current in all winding sections would be again nearly the same depending on the maximum transverse field of each section.

This optimization is illustrated in Fig. 3, where the spezific current density in the superconductor is plotted versus the field intensity and related to the spezific short sample characteristic.

At 650 A a maximum field strength of 73 transverse to the innermost layer would be achieved, if 4 coils of each type are combined to form a compact setup.

The maximum field transverse to the second winding section would then be about 53 KG etc. The field vectors at the coil edge do not exceed the corresponding values at the midplane.

The smallest coils SSp 50 are wound with stabilized half-inch-wide Nb_3Su tape. Two coils of this type tested so far consist of GE tape 22CYo 30, a third one contains an inner section with RCA tape and an outer section with GE tape.

Each coil is composed of two double pancakes (modules) connected in series. The inner sections are represented by tape shunted 0.5 mm thick copper cylinders. Liquid helium is allowed to flow along the edges of the pancakes and also to the inner surface of the copper cylinder. The bare Nb_3Sm tape is insulated by a thin Kapton foil, which is bifilar wound with the superconducting tape.

During the test programme the cooling was intensified by extending the cooling channels but without any remarkable effect.

Different current leads for all three coil types were developed. They will be described in more detail in a seperate report.

2. Test results

A number of specific test results are summarized in Table II and related to the design data.

Type	Number of coils	Current A	Field centre kG	Field max. kG	Current density A/mm²	
SSP 50	4	320	60	70		design
SSP 50	1/2	535	51	69	428	test
	1	305	50	60	244	"
	2	280	53	62	224	"
SSP 170	4	1000	50			design
SSP 170	1	1350	27	43	191	test
	4	1070	53	57	151	"
SSP 350	4	650	36			design
SSP 350	2	725	24	40	142	test
Combination SSP 50 + SSP 170 4 + 4		220 1000	91			design
Combination SSP 170 + SSP 350 4 + 4		650	70			design
Combination SSP 50 + SSP 170 + SSP 350		200 650	107			design

Table II Design data and test results

2.1 SSP 50

Each module (1/2 coil) was tested seperately. Some of them first showed poor performance. After the tests we detected cracks and nonuniformities in the tape. We therefore cut off some pieces and wound and rewound the coils several times. Finally we achieved currents between 430 and 535A, which agree fairly well with short sample values. It may be of interest to note that particularly the coil section which has most joints inside the winding reached the highest current.

After some modules were combined to form one-coil or two-coil units, the performance decreased noticably but nevertheless remained near the design data.

The test results achieved so far are summarized in Fig. 4, where the maximum current and field values are related to the short sample characteristic.

The coils are sensitive to fast current variations. It always took several minutes to reach the maximum current.

All single coils and their combinations were quenched many times and even at the highest currents no damage could be observed. Depending on the current and on the number of coil sections used the decay time of the current during a quench varies between 1/5 and 1/2 sec.

The tests described are not yet complete. Performance may be improved in future runs.

2.2 SSP 170

The coil type SSp 170 was tested in two stages. First, one seperated coil was powered up to 1350 A maximum current, thus producing a maximum field of 43 KG. This coil was also quenched several times at currents between 1250 and 1350 A. The quenching always started very slowly with a time constant of about 10 sec.

Therefore the magnetic energy could always be discharged across a simple protection circuit without any serious troubles. Though the voltage across the protection resistance did not exceed 50 V, the efficiency was more than 80 %.

During the following test procedure 4 coils of the same type were combined to form a compact coil system of 32 cm axial length. After several quenches a maximum current of 1070 A was reached. This current produced a field of 53 KG on the axis and about 57 KG near the innermost layer. The magnetic energy stored in this case was about 150 KJ.

2.3 SSP 350

Only a combination of two coils of the type SSp 350 consisting of Supercon cables has been tested so far.

The quenching currents varied between 650 and 725 A. Like the SSp 170-coils, the quenching again started very slowly, thus allowing most of the energy to be discharged to a resistance on the outside of the cryostat.

All these cable-coils are quite insensitive to fast current changes. The current could be increased to the maximum value in less than 1 minute.

The test results described above are summarized in Fig. 5, where the maximum values are related to the short sample charateristic of the corresponding cables.

Particularly in the case of SSp 170, there is sufficiently good agreement between the coil and sample values.

As mentioned above, the coils are not fully stabilized, which means that propagation of the normal zone could not be prevented. The recovery current can be assumed to be 40 % to 60 % of the currents actually achieved.

The specific costs of the applied NbTi superconductors are plotted versus the field strength in Fig. 6.

If the costs of the cables used for both of the large coil types are divided by their cable length and their test current, we get specific values, which may be compared to those short sample values. The coil values are indicated by dots in the same diagramm.

Caused by the optimization described above the specific costs of the coil type SSp 170 are lower than those of the cheapest cables, if they are based on maximum test currents.

3. Conclusions

These investigations on large superconducting coils show that they can be used for various applications in plasma physics. Coils of such medium size need not be fully stabilized even if they are subject to heavy duty.

It seems possible to provide standard module-type coils, which may be applied in various modifications.

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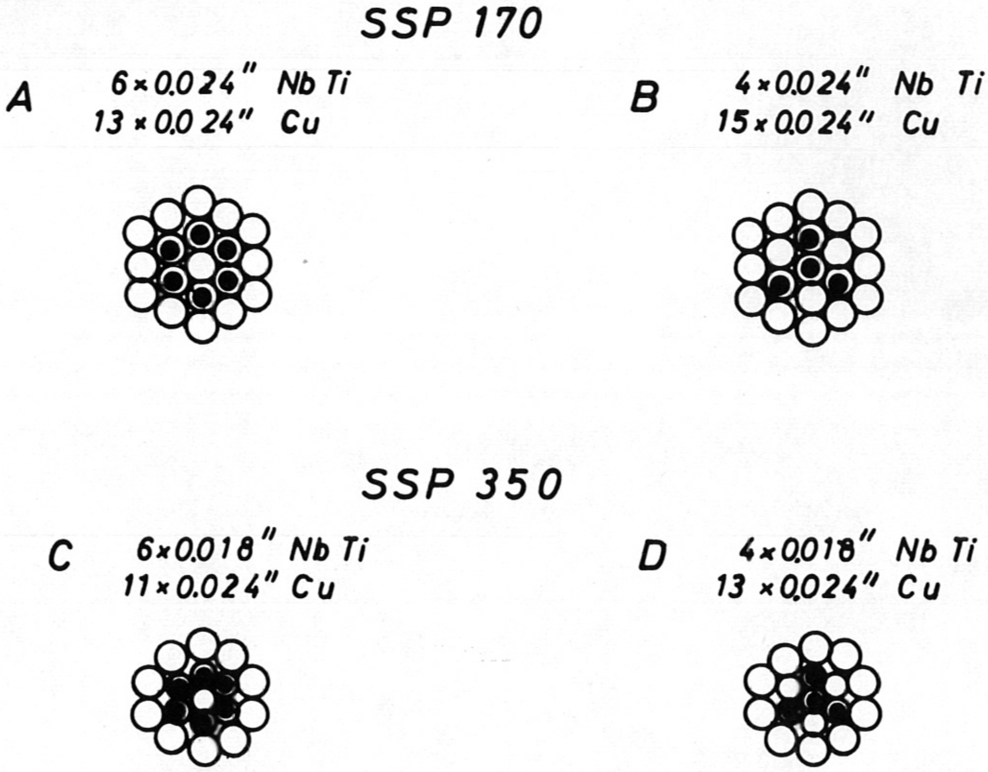

Fig. 1

Composite superconducting cables (SUPERCON)

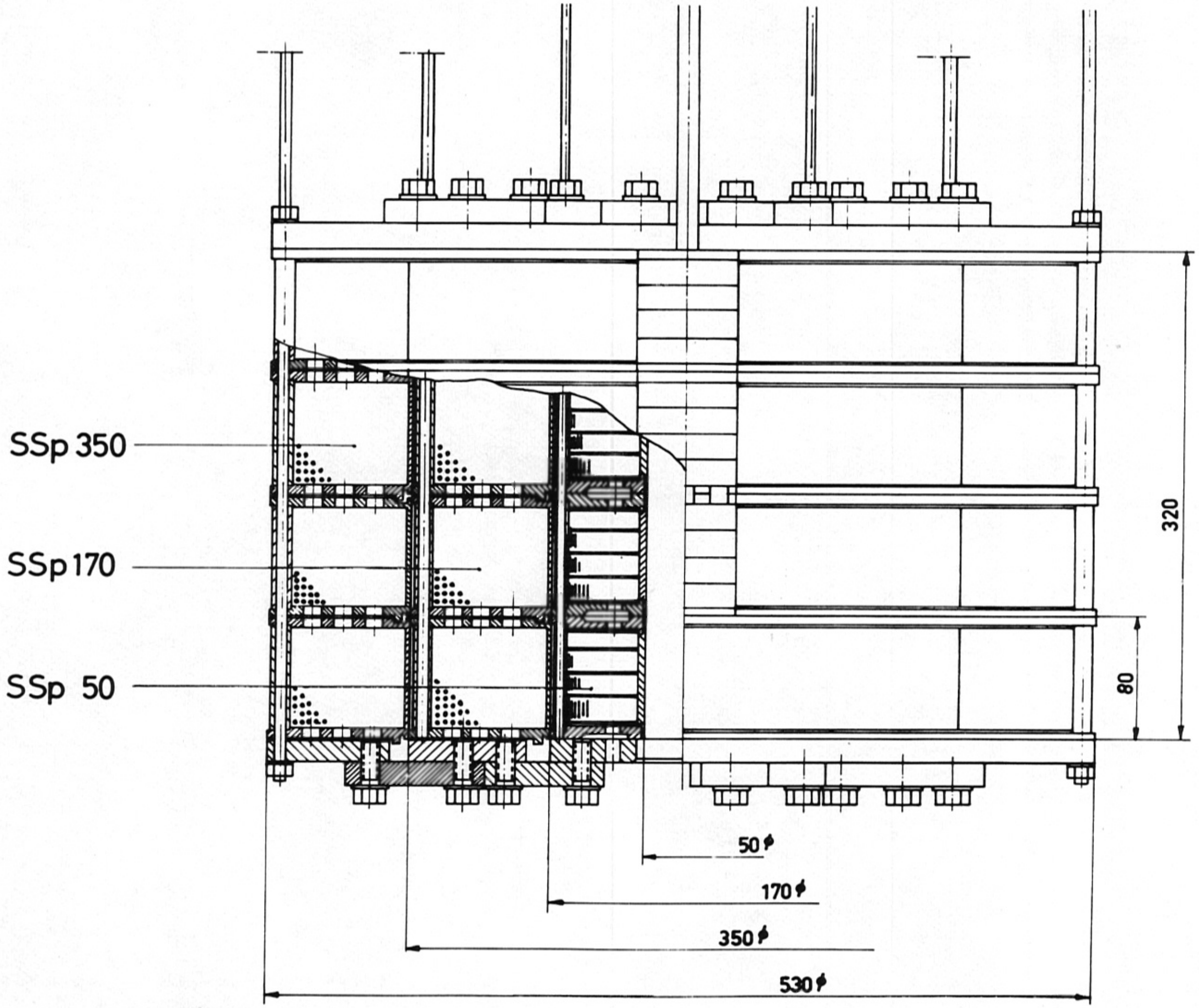

Fig. 2 Combination of superconducting coils SSp 50 SSp170 SSp350

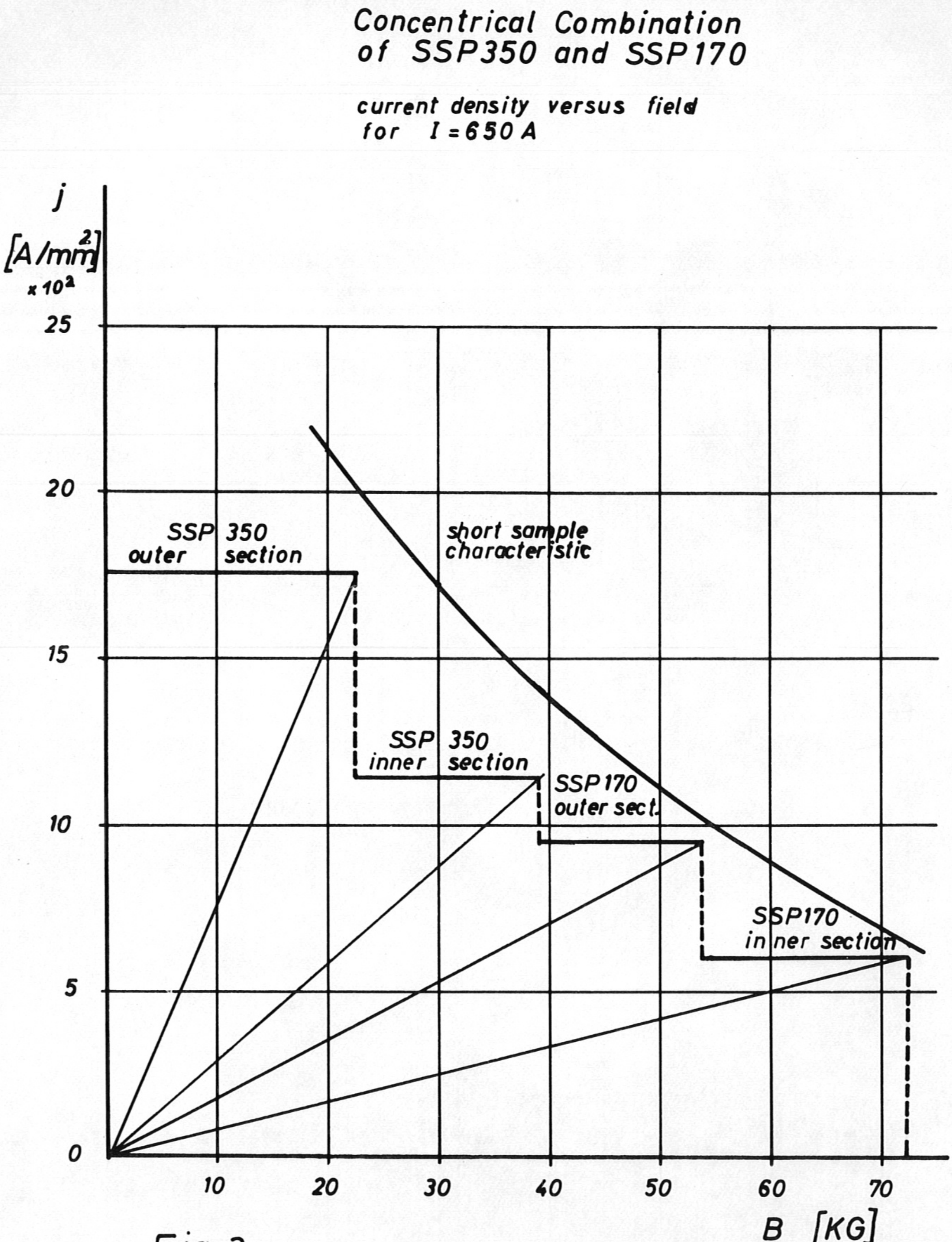
Concentrical Combination
of SSP350 and SSP170
current density versus field
for I = 650 A
j
[A/mm²]
x 10²
25
20
15
10
5
0
10
20
30
40
50
60
70
B [KG]
SSP 350
outer section
short sample
characteristic
SSP 350
inner section
SSP170
outer sect.
SSP170
inner section

Fig. 3

SSP 50 Test Results

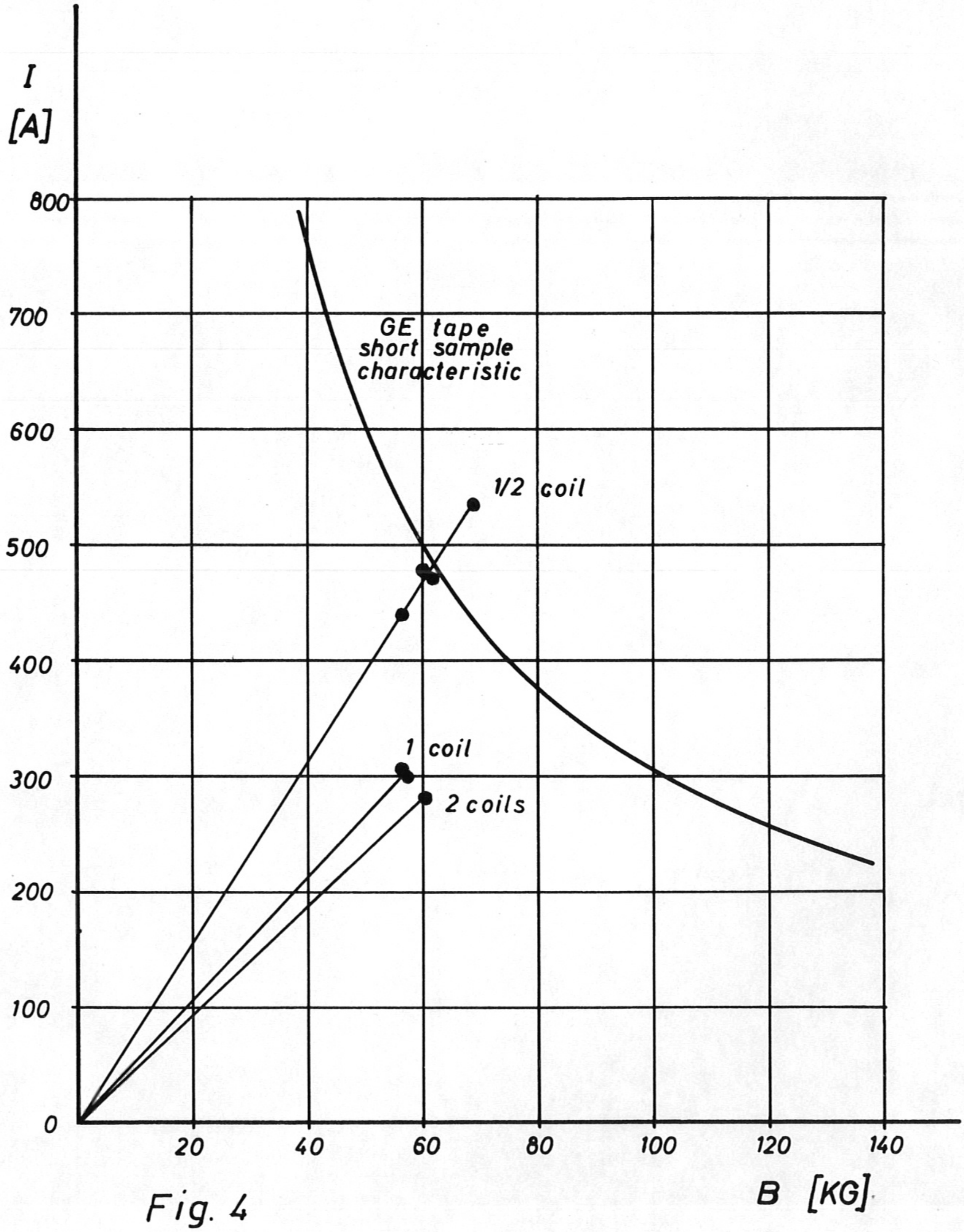

Fig. 4

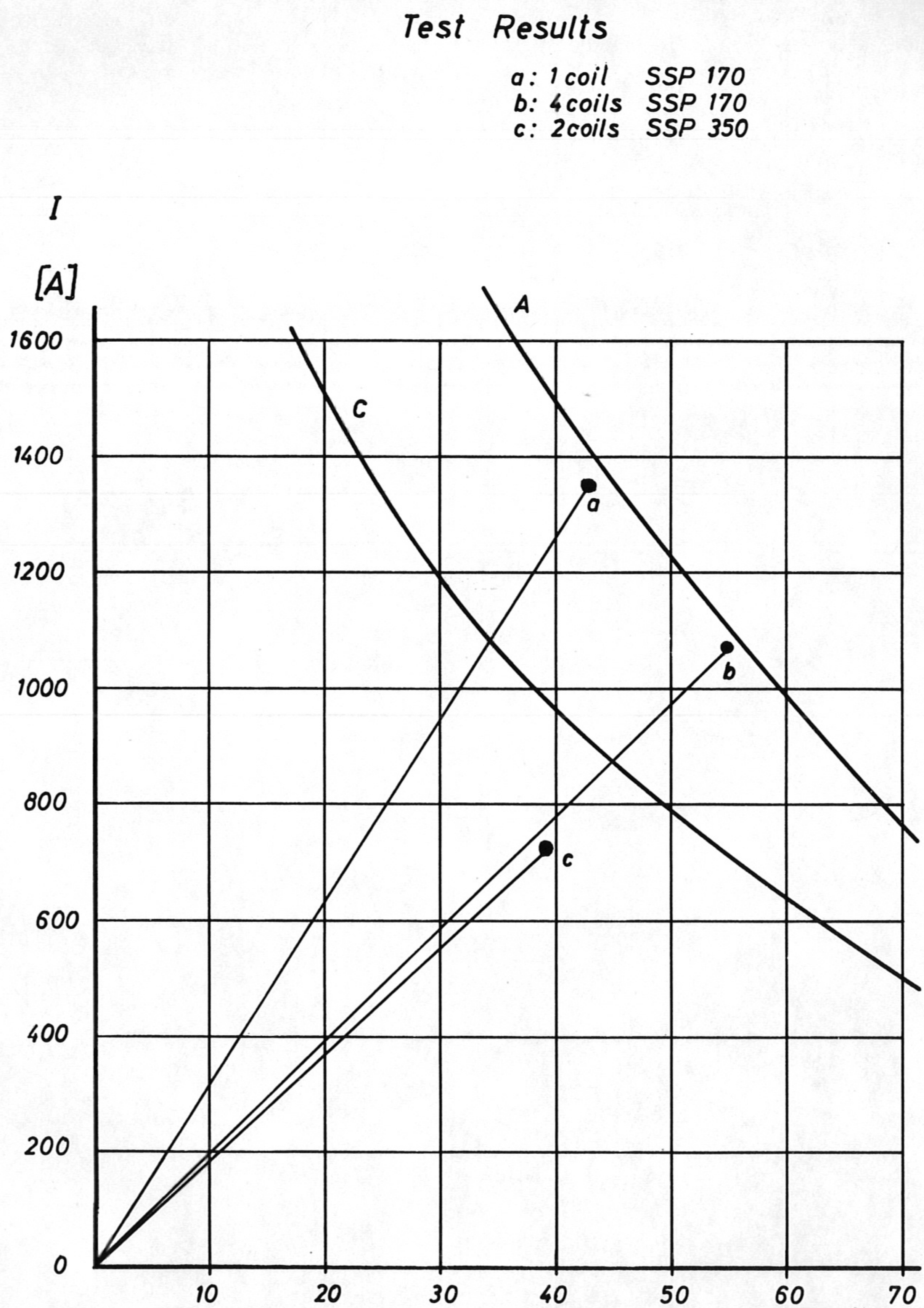
Test Results
a : 1 coil SSP 170
b: 4 coils SSP 170
c: 2 coils SSP 350
I
[A]
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
70
B [KG]
A
C
a
b
c

Fig. 5

Spezific Costs

from short samples: A: cable 6 × 0.024" (SUPERCON)
B: " 4 × 0.024" "
C: " 6 × 0018" "
D: " 4 × 0018" "

from coil tests: a: 1 coil SSP 170
b: 4 coils SSP 170
c: 2 coils SSP 350

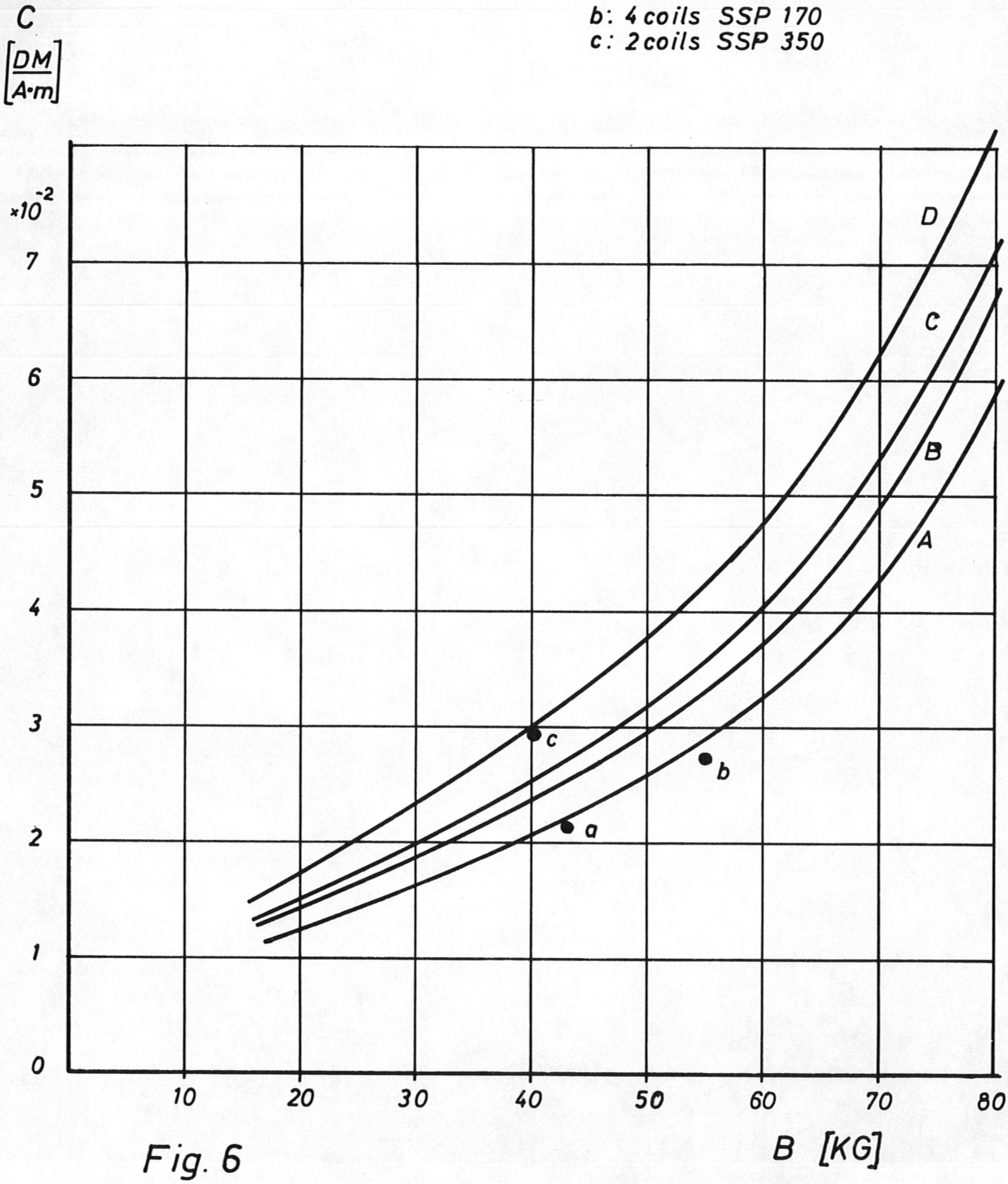

Fig. 6

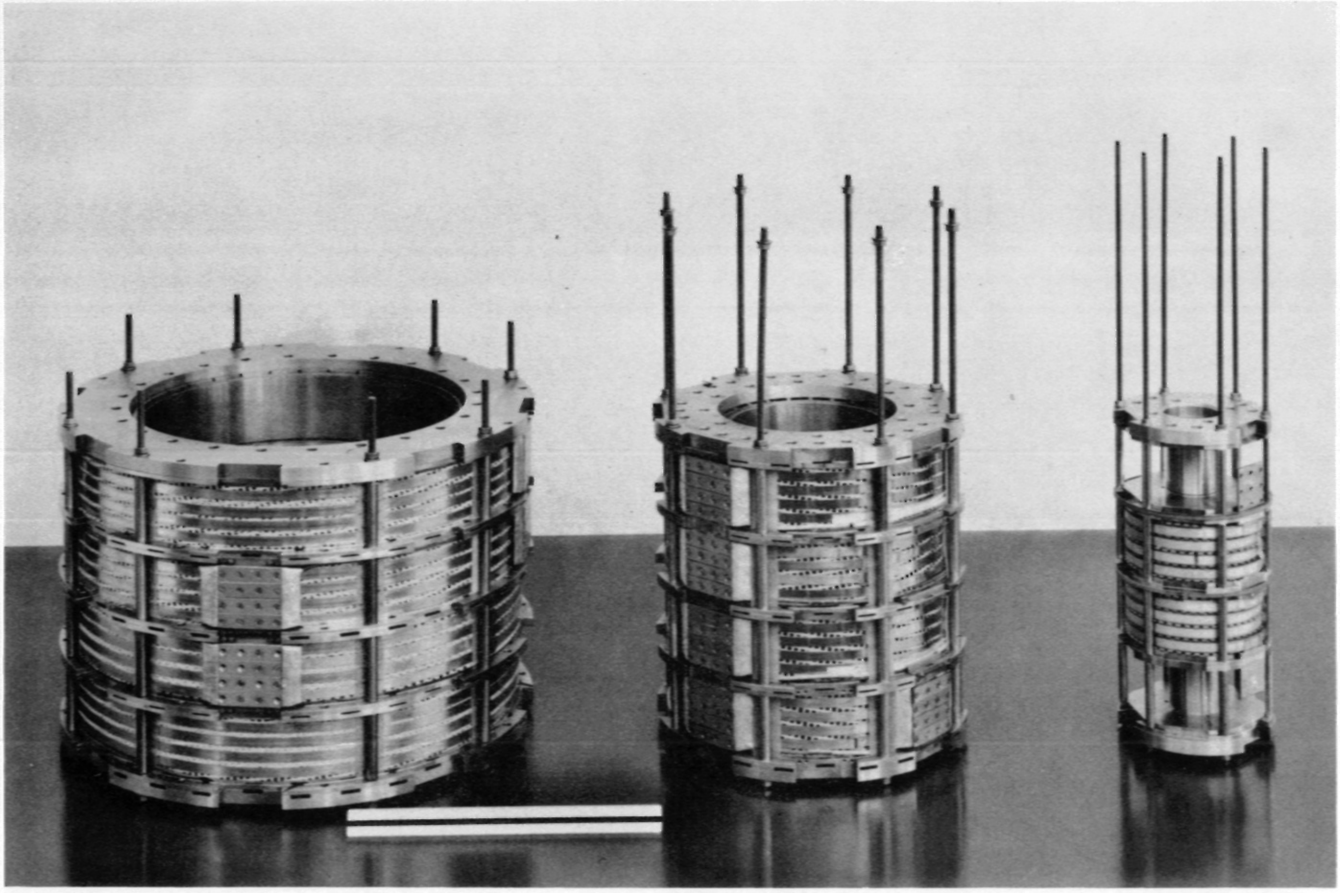

Fig. 7

4coils SSp 350, 4coils SSp170, 2 coils SSp50

(from left to right)