

A simple superconducting system which allows almost loss-less ac magnetic field to be generated in the kilo-oersted region and in the frequency range from dc up to more than 1 kHz is described. The behaviour of commercially available superconducting wires and the influence of winding of the coils are also considered.

A loss-less superconducting kilo-oersted ac magnetic field system

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A growing interest has developed in the behaviour of superconductors in alternating fields, mainly due to the possible use of superconducting materials for large scale applications.¹ Investigations on this topic on a laboratory scale are usually carried out by induction methods. These experiments can be roughly divided into two groups: in the first the samples are subjected to large amplitude alternating fields (up to 2 kOe), in the second smaller amplitudes biased by a dc field are used. Both methods have their specific merits and disadvantages. In the latter for instance the determination of the time independent component of the average induction inside the sample may be a problem.

So far both liquid nitrogen cooled and superconducting coil systems have been used for generating the applied field. Obviously liquid nitrogen cooled systems require much larger power supplies than the superconducting ones.

For the first type of experiments the field coils can either be driven directly from the power supply² or to overcome the high voltages needed at higher frequencies, by a resonance technique,³ which will be discussed in the next section in more detail. The second type of experiments can be performed in two ways: by separate coil systems,⁴ each of them generating one of the components H_0 and $h \cos \omega t$ of the total field or by feeding a modulated current^{5,6} into one coil. In this way the problem of decoupling the two coil systems magnetically can be avoided. But losses may still be present in the coil.⁵

In this paper a description is given of a simple superconducting system which enables us to generate almost loss-less ac magnetic fields in the kilo-oersted region and in the frequency range from dc up to more than 1 kHz. The behaviour of various commercially available superconducting wires and the influence of the winding of the coils are also investigated.

General principle

The design starts from the transformer principle without core (Fig. 1). Both coils are made of superconducting wire; the secondary coil is the field coil. The ac field is generated by means of the primary coil. The field coil can be brought into resonance with the help of an appropriate condenser,

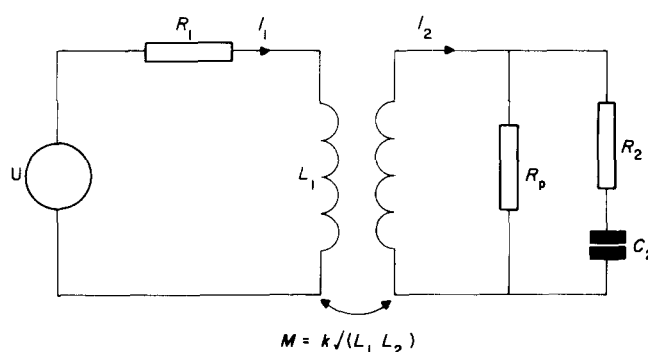


Fig. 1 Plan of the circuit

C_2 , connected in parallel. This condenser, which is placed outside the cryostat, consists of a set of parallel condensers in order to reduce the electrical resistance and in this way the total series resistance in the resonance circuit has been minimized. When the transformer is operated at its resonance frequency only (a small amount of) power has to be supplied in order to compensate for the losses in the secondary circuit, mainly in the condenser. In this way small and cheap power supplies can be used. Evaporation of the helium is mainly due to dissipation in the current leads of the secondary circuit.

Current ratio and resonance frequency

The current in the field coil is induced by a small primary coil which has been wound around the field coil. In Fig. 1 the fundamental outline of the system is shown. R_1 represents the total internal resistance of the power supply and a load resistance; R_2 is the total series resistance of the resonance circuit consisting of three parts: a small resistor (0.01 Ω) to measure the secondary current I_2 , the series resistance of the condenser, and the resistance of the current leads.

The losses in the field coil have been accounted for by a resistance R_p parallel to the field coil.

To calculate the current ratio I_2/I_1 and the resonance frequency of the field coil the usual calculation technique has been applied; reference can be made to any elementary text book on network analysis.

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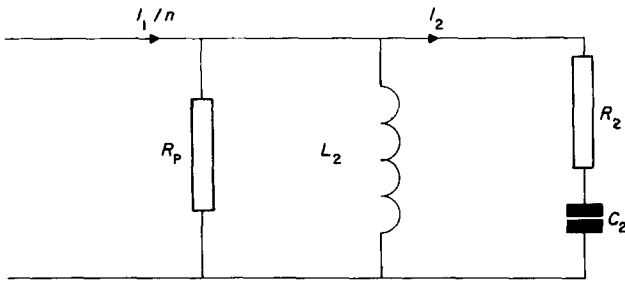


Fig. 2 Transformed plan of the circuit

The essential part of the fundamental scheme of Fig. 1 can be transformed into the one presented in Fig. 2. The primary current I_1 has been transformed into: $(1/n)I_1$ with $n = (1/k)\sqrt{(L_2/L_1)}$; L_2 and L_1 are the self-inductances of the secondary and primary coil respectively and k the coupling coefficient. The frequency dependent current ratio can be written

$$\frac{I_2}{I_1} = \frac{1}{n} \frac{R_p}{R_p + R_2} \times \frac{\left(\frac{j\omega}{\omega_0}\right)^2}{1 + \frac{j\omega}{\omega_0} \frac{1}{Q} + \left(\frac{j\omega}{\omega_0}\right)^2}$$

with

$$\frac{1}{\omega_0^2} = L_2 C_2 \left(1 + \frac{R_2}{R_p}\right)$$

and

$$\frac{1}{Q} = \left(\frac{L_2}{R_p} + R_2 C_2\right) \omega_0$$

For the resonance frequency, which is the frequency where $|I_2/I_1|$ has its maximal value, it is found that

$$\frac{1}{\omega_r^2} = L_2 C_2 - \frac{R_2^2 C_2^2}{2} - \frac{L_2^2}{2R_p^2}$$

In practice $R_p \gg R_2$ and $\omega_r \sim \omega_0$ so we can write

$$\left|\frac{I_2}{I_1}\right|_{\max} \sim \frac{Q}{n}$$

Experimental results

Dependance of $|I_2/I_1|_{\max}$ on I_2 . The first measurements were carried out on a coil system consisting of two secondary and two primary coils wound, on top of each other, on the same coil holder. The diameter of the celeron coil holder was 3 cm. The most important data about the coils are presented in Table 1.

The first experimental results can be summarized as follows:

- (a) $|I_2/I_1|_{\max}$ changes linearly with $\sqrt{L_1}$
- (b) $|I_2/I_1|_{\max}$ is almost independent of I_2 when the secondary coil consists of one layer
- (c) $|I_2/I_1|_{\max}$ strongly decreases with increasing I_2 when the six layer secondary coil is used.

Result (a) can be understood in the following way.

By taking $R_p \gg R_2$ we get

$$\frac{1}{Q} = \frac{1}{R_p} \sqrt{\frac{L_2}{C_2}} + R_2 \sqrt{\frac{C_2}{L_2}} \quad \text{and with } n = \frac{1}{k} \sqrt{\frac{L_2}{L_1}}$$

and so

$$\left|\frac{I_2}{I_1}\right|_{\max} = \frac{Q}{n} = \frac{k \sqrt{L_1} C_2}{\frac{L_2}{R_p} + R_2 C_2}$$

which denotes that, in accordance with the experimental results $|I_2/I_1|_{\max}$ is proportional to $\sqrt{L_1}$.

With regard to the results mentioned in (b) and (c) it may be noted that the inner layers of the six layer coil are subjected to the alternating magnetic field of the outer layers; eddy current losses are generated and so the maximum value of I_2 will be reduced.

Since the one layer coil has no inner layers, eddy current effects will play a minor role and so $|I_2/I_1|_{\max}$ will be independent of I_2 .

Loss reduction; results on coils, made of thin superconducting wire with CuNi matrix

The Vacuumschmelze F60,0.20 superconducting wire consists of 60 superconducting filaments of NbTi in a matrix of copper. Eddy current losses can be reduced by using a matrix material with high electrical resistivity. By applying as few layers as possible for a given number of turns per unit

Table 1

Type	No of turns	No of layers	Length	Self inductance	Diameter of wire	Type of wire
Primary	93	1	5 cm	172 μ H	0.50 mm	Niomax S25/50
Primary	186	1	10 cm	360 μ H	0.50 mm	Niomax S25/50
Secondary	415	1	10 cm	2 mH	0.20 mm	Vacuumschmelze F60, 0.20
Secondary	2405	6	10 cm	51 mH	0.20 mm	Vacuumschmelze F60, 0.20

Table 2

Type	No of turns	No of layers	Length	Diameter of wire	Type of wire	Indicated in Fig. 5
Primary	172	1	5 cm	0.25 mm	Niomax FM A61/25	a (at 4.2 K)
Primary	344	1	10 cm	0.25 mm	Niomax FM A61/25	b (at 1.4 K)
Secondary	1530	1	10 cm	0.05 mm	Niomax CN A61/05	
Primary	171	1	5 cm	0.25 mm	Niomax FM A61/25	c (at 4.2 K)
Primary	342	1	10 cm	0.25 mm	Niomax FM A61/25	d (at 1.4 K)
Secondary	2848	2	10 cm	0.05 mm	Niomax CN A61/05	
Primary	94	1	5 cm	0.50 mm	Niomax S 25/50	e (at 4.2 K)
Primary	188	1	10 cm	0.50 mm	Niomax S 25/50	f (at 1.4 K)
Secondary	5860	4	10 cm	0.05 mm	Niomax CN 61/05	

length, the magnetic field that is felt by the superconducting wire, is minimized. On account of these considerations three coil systems have been made in which the secondary coil was wound with a superconducting wire with a diameter of 0.05 mm. This wire consists of 61 filaments in a matrix of CuNi, the resistivity of which is more than a factor of 100 higher than Cu. Table 2 gives more data about these coil systems.

Measurements on these coils showed that the ratio $|I_2/I_1|_{\max}$ is almost independent of I_2 up to a certain value of I_2 which we denote by I_{\max} ; at this value of I_{\max} this ratio decreases by a factor of more than a hundred. Obviously the superconducting state has been disturbed at that value of I_2 . In Fig. 3 the values of I_{\max} have been plotted as a function of frequency. From these curves it can be seen that the maximum current through the field coil, I_{\max} , has a smaller value when the number of layers of the coil is larger, and, moreover, that better results are obtained at lower temperatures. This is also shown in Fig. 4 where I_{\max} is plotted against temperature at a frequency of 31 Hz with a field coil, consisting of one layer of 1530 turns. It should be noted that in the low frequency limit ($\nu < 10$ Hz) the values of I_{\max} are only slightly smaller than the maximum dc currents in the secondary coil.

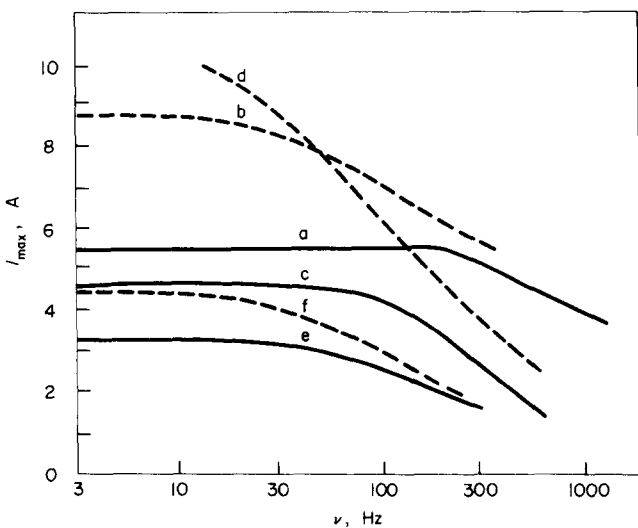


Fig. 3 I_{\max} as a function of frequency and temperature for the coils indicated in Table 2

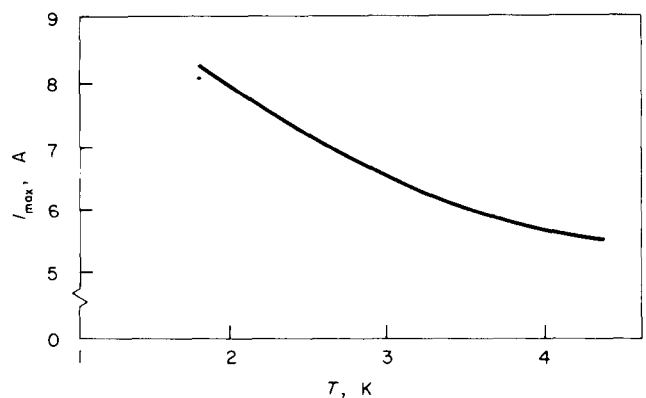


Fig. 4 I_{\max} as a function of temperature for the secondary coil with 1530 turns; $\nu = 31$ Hz

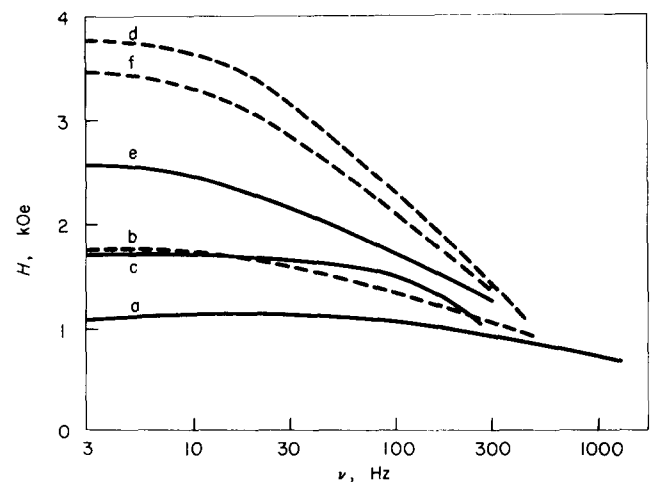


Fig. 5 Maximum amplitude of the field as a function of frequency and temperature for the coils indicated in Table 2

In Fig. 5 the maximum magnetic fields, which can be achieved with each of the three coil systems, are shown as a function of frequency. These magnetic fields are estimated from the currents measured in the secondary coils. At lower frequencies the larger primary coils are used for driving the systems.

The power supply used in these measurements was made with a RCA 2000H integrated circuit.

Concerning the value of I_{\max} we observed a phenomenon which has not yet been explained. When the coils are cooled down to liquid helium temperature for the second time, the values of I_{\max} are reduced to about 90% of the original values. After warming up and cooling down again no further changes in these reduced values of I_{\max} have been observed. The curves in the figures are related to these reduced values.

Conclusion

The experimental results, presented in this paper, show that the resonance method described provides a simple and cheap system for generating kilo-oersted ac magnetic fields. A disadvantage is that the capacitor in the resonance circuit should be changed in order to change the frequency and that, at very low frequencies, an enormous condenser would be required. In this case however the field coil can be connected directly to the power supply because the impedance

of the field coil is sufficiently small at low frequencies. When a capacitor is used, the losses can be considerably reduced by placing the condenser in the helium bath.

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energy analysis

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The 14 chapters of this book first appeared as papers in the journals *Energy Policy* and *Food Policy*. They form a snapshot of ongoing research, a record of the growing pains of a fledgling subject. The book reflects the debates and controversies about the strengths and weaknesses of energy analysis as an alternative to traditional economics for dealing with resource depletion problems.

contents

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