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Francken

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[54] **CIRCUIT ARRANGEMENT COMPRISING A PLURALITY OF SEPARATELY ENERGIZABLE SUPER-CONDUCTIVE COILS**

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[58] **Field of Search**....340/173.1; 323/44 F; 307/113

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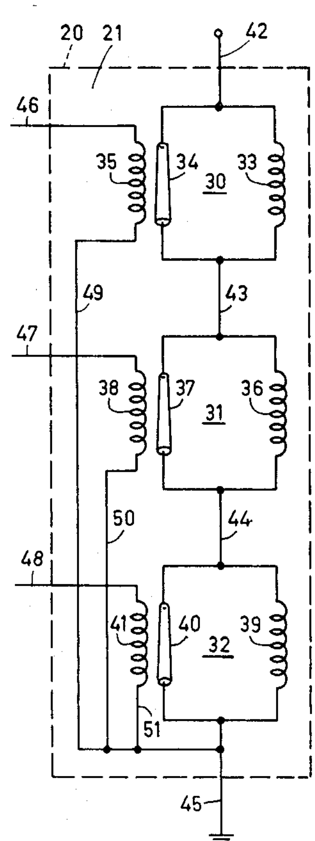
[57] **ABSTRACT**

A superconductor circuit comprising a plurality of superconductor coils each of which is shunted by a superconductor switch to form a plurality of closed loop circuits. The circuits are series connected between the input terminals of a current source. Selective operation of the shunt switches in combination with an adjustment of the supply current permits one to set up individual persistent currents of different magnitudes in each closed loop circuit. This construction requires only two current leads to supply all of the persistent currents for the coils thereby reducing thermal leakage between the superconductive container and the environment.

11 Claims, 2 Drawing Figures



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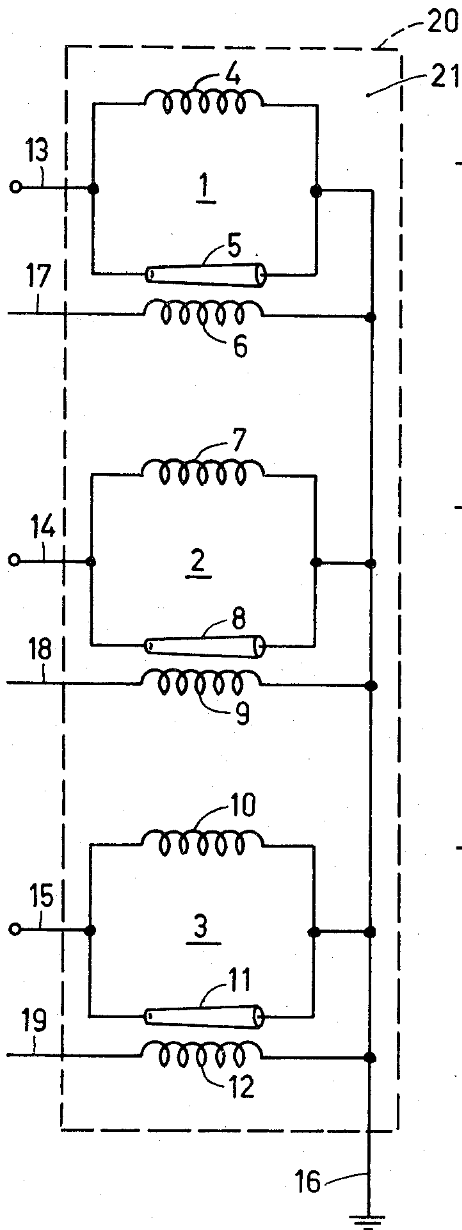

Fig. 1

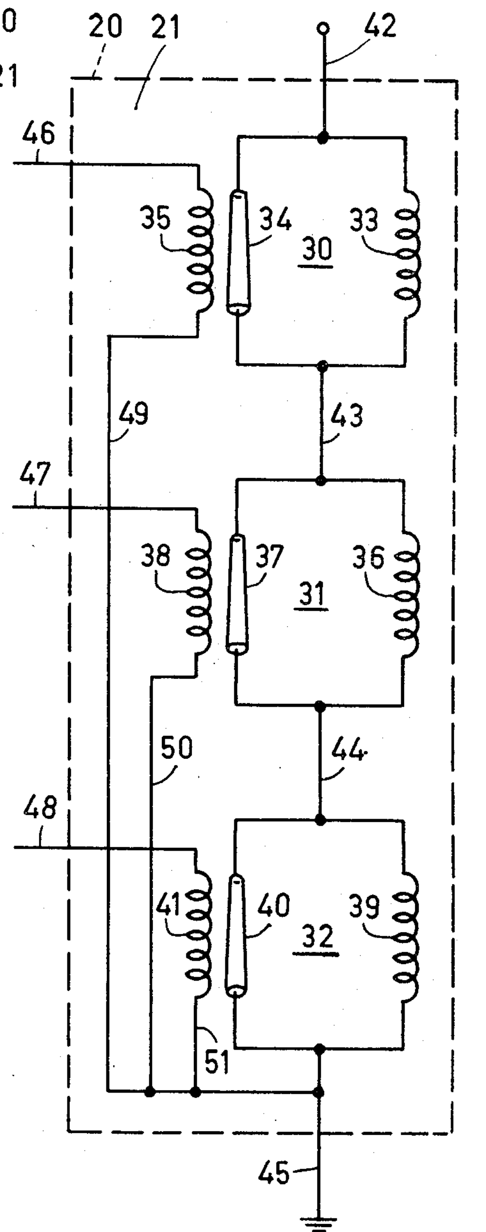

Fig. 2

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CIRCUIT ARRANGEMENT COMPRISING A PLURALITY OF SEPARATELY ENERGIZABLE SUPER-CONDUCTIVE COILS

This invention relates to a circuit arrangement comprising a plurality of separately energizable, superconductive electromagnetic coils, each coil together with an associated superconductive switch forming a closed loop current circuit.

The energization of such a superconductive coil results in a persistent current through the current circuit formed by the coil and the switch, the combination then being completely superconducting. In many uses, for example, in an electron microscope in which the coils are formed by the electromagnetic lenses, persistent currents of high intensity are desired. Where high currents are desired, it is indeed advantageous to employ persistent currents because this enables one to solve adequately the heat problem. The use of superconductive persistent currents also provides the possibility of obtaining a high degree of constance of the current intensity even with high currents. The coils of such an arrangement have to be individually energizable. In order to supply the currents to each of the electromagnetic coils individually, known arrangements comprise a separate supply wire for each coil, whereas a common outlet conductor is provided for all of the coils. These conductors have to be able to convey said high currents so that they must have a comparatively large diameter. Through these conductors a large amount of heat will therefore flow towards the cooled space, in this case, a space kept at the low temperature required for superconduction by liquid helium. As a consequence the liquid helium evaporates and the arrangement cannot operate uninterruptedly for a long time or during operation liquid helium has to be replenished. Liquefaction of helium is an expensive process so that continuous operation of an apparatus operating on persistent currents is costly. If a great many small superconductive coils are included in, for example, storage elements of computers, the thermal leakage of each supply wire is small, it is true, but due to the large number of supply wires the overall thermal leakage is nevertheless considerable.

Apart from the supply conductors for the subsequent persistent currents, a control wire is required if switches having a control winding are used. The intensities of the control currents for the switches are comparatively low and the control wires may therefore be thin so that they introduce only a comparatively small thermal leakage.

The invention has for its object, while maintaining the possibility of energizing the coils individually, to provide a reduction of thermal leakage and a circuit arrangement of the kind set forth is characterized in that the superconductive, electromagnetic coils are connected in series and in that for the currents to be supplied from without to the superconductive coils only two current conductors are provided.

Consequently, apart from an outlet conductor only one supply conductor is provided for conveying the energizing currents of the coils independently of the number of coils. Particularly when many coils are used in an arrangement the thermal leakage is thus considerably reduced. By connecting in parallel with each coil in the arrangement in accordance with the invention a superconductive switch, it is thus also possible to energize the individual coils by the current of the desired intensity.

One embodiment of an arrangement in accordance with the invention will be described hereinafter with reference to the drawing, in which;

FIG. 1 shows a known circuit arrangement comprising three individually energizable, superconductive coils and

FIG. 2 shows a circuit arrangement in accordance with the invention also comprising three individually energizable coils.

The circuit arrangement shown in FIG. 1 comprises three closed current circuits **1**, **2** and **3**, but any number exceeding one may be chosen. The current circuit **1** includes a superconductive, electromagnetic coil **4** and a superconductive switch **5** having a control element **6**. The current circuit **2** comprises likewise a superconductive, electromagnet **7** and a superconductive switch **8** having a control element **9** and the current circuit **3** includes a superconductive electromagnet **10** and a superconductive switch **11** having a control element **12**.

The superconductive electromagnets may be formed by coils constituting lenses of an electron microscope, of an ion beam apparatus or of a particle accelerator. They may alternatively be formed by superconductive electromagnetic storage elements of a computer. The superconductive switches may be of any known type, for example, that described in an article in "The Review of Scientific Instruments," Vol. 35, No. 6, pages 733 to 737, that is to say, both thermal and magnetic switches with or without control wires.

The current circuits **1**, **2** and **3** are connected on the one hand to supply leads **13**, **14** and **15**, respectively, and on the other hand to a common outlet conductor **16**. The control elements **6**, **9** and **12** are connected on the one hand to control wires **17**, **18** and **19**, respectively, and on the other hand also to the common outlet conductor **16**.

In view of the independent position of each of the current circuits **1**, **2** and **3** in the arrangement of FIG. **1** it will be obvious that in this arrangement the coils **4**, **7** and **10** can be energized independently of each other. With each of the coils this process evolves in an identical manner and it may suffice to describe the operation for one coil, for example, coil **7**. Starting from the superconducting state of both the coil **7** and the switch **8**, first the switch **8** is brought from the superconducting state into the normal state by means of a control current passing via the control wire **18** and the output conductor **16** through the control element **9**. This means that the switch **8** is open and does not allow current to pass. A current slowly increasing its strength and emanating from a current source connected to the supply lead **14** and to the outlet conductor **16** is compelled to pass through the coil **7**. This current is raised to a desired current strength and energizes coil **7**. If the control current through the control element **9** is switched off, the switch **8** again becomes superconducting. If, subsequently, the strength of the current supplied between the lead **14** and **16** is slowly reduced to zero, a persistent current of the initial strength will flow through the current circuit **2** since the magnetic field of the coil **7** counteracts current intensity variations and this coil is short-circuited by switch **8**. If it is desired to change the intensity of the persistent current through circuit 2, first the persistent current passing from right to left in FIG. 1 through the element 8 is compensated by a current supplied via the lead 14 having the same intensity. This supplied current, as long as the switch 8 is superconducting, will flow completely through said switch and will not pass through coil 7 because its impedance now also counteracts current intensity variations. If the switch 8 does not convey current, it may be opened by means of a control current. A variation of the supplied current is then imposed on coil 7. When the current intensity has reached the desired level, the control current of the control element is switched off, after which the switch becomes superconducting and the new current through circuit 2 becomes persistent. Through each of the coils 4, 7 and 10 a persistent current can be produced or varied in intensity in exactly the same manner. A field strength variation may be introduced by means of an auxiliary coil. In this case the main current remains persistent. Because the variations are comparatively small thin current conductors may suffice for the auxiliary coil.

FIG. 2 shows an embodiment of a circuit arrangement in accordance with the invention also having three coils. This arrangement comprises three closed loop current circuits 30, 31 and 32, but any other number exceeding one may be chosen. The current circuit 30 comprises a superconductive electromagnetic coil 33 and a superconductive switch 34 having a control element 35. The current circuit 31 likewise comprises a superconductive electromagnetic coil 36 and a superconductive switch 37 having a control element 38 and the current circuit 32 comprises a superconductive electromagnetic coil 39 and a superconductive switch 40 having a control element 41. The current circuits 30, 31 and 32 form a series connection having a common supply lead 42, mutual connections 43 and 44 and a common outlet conductor 45, which may be formed by the mass of a device, part of which is formed by the circuit arrangement. The control elements 35, 38 and 41 connected in parallel with the switches 34, 37 and 40 respectively are connected on the one hand to supply leads 46, 47 and 48 respectively and on the other hand via connections 49, 50 and 51 respectively to the common outlet conductor 45. Also in this arrangement each of the coils 33, 36 and 39 can be energized independently of the others, which will be explained hereinafter. In this superconducting state the impedance of the coils 33, 36 and 39 counteracts current intensity variations in the coils and the current emanating from a current source connected between the leads 42 and 45 will pass through the three switches. If one of the switches, for example, switch 37, is opened as a result of a control current passing through the control element 38, a current passing through the supply lead 42, the switch 34 and the connection 43 is compelled to flow through the coil 36, which is thus energized. By rendering again superconducting the circuit element 37 and by reducing the supplied current intensity through the circuit 31 slowly to zero said current becomes persistent. A current supplied via the connection 43 under these conditions does not affect in any way the coil 36 owing to the impedance of the coil 36 and to the superconducting state of the switch 37, so that in the same manner as described for coil 36 the coils 33 and 39 can be energized by persistent currents through the circuits 30 and 32. If it is desired to vary the current intensity in one of the circuits, starting from the state in which each of the three circuits conveys a persistent current, a current is supplied from the terminals 42 and 45. This current is equal to the persistent current passing through the circuit concerned. This supply current permits the opening of the switch concerned without affecting the coil currents. An increase or a decrease of the supply current results in a current variation through the coil concerned, after which the new current can again become persistent. Each of the coils 33, 36 and 39, like the coils 4, 7 and 10, respectively, of FIG. 1, can therefore be energized independently of the others. From FIG. 2 and from the method of energization of the coils described above it will be apparent that this possibility does not depend upon the number of coils. For field intensity variations again an auxiliary coil may be employed.

In the Figures a broken line 20 surrounds a domain 21 in which the temperature can be kept at such a low level that superconductivity is possible. In most cases the space will be filled or surrounded by a liquid helium bath, which permits of attaining a temperature of 4° to 5° K. The partition 20 is pierced, as is shown in FIG. 1, by three supply leads 13, 14 and 15, three control wires 17, 18 and 19 and one outlet conductor 16, and as shown in FIG. 2 by one supply lead 42, three control wires 46, 47 and 48 and one outlet conductor 45. In more general terms: the known arrangement comprising n coils requires n supply leads, one common outlet conductor and n control wires. The arrangement according to the invention requires one supply lead, one outlet conductor for the current supply to all current circuits and n control wires. The control wires, as compared with the supply leads, are thin since the control windings require current of not more than a few milliamperes so that they contribute only to a small extent to the thermal leakage, whereas with n coils the ratio of the thermal leakage is $2:(n+1)$. There are also known superconductive switching elements operating without control wires, but they are adjustable, for example, by direct external inductance or the supply of radiation heat. In these cases the control wires are dispensed with for the two arrangements. The outlet conductor is frequently formed by the mass of the apparatus equipped with superconductive coils so that no additional thermal leakage is introduced. Since currents up to, for example, 50 amperes may have to be supplied, the supply leads have to be thick. Persistent currents through electromagnetic imaging lenses of apparatus operating on charged particles frequently have to be of said order of magnitude as correction lenses in such apparatus.

In apparatus comprising many small superconductive electromagnetic elements, for example, superconductive storage elements in computers, the gain in heat insulation is due to the high amount of saving of the number of supply leads in the arrangement embodying the invention. It is more important than with the use of coils requiring high persistent currents to eliminate the thermal leakage via the control wires by the choice of the switches, at any rate in a circuit arrangement in accordance with the invention in which the contribution of the control wires to the thermal leakage is accordingly higher than in the known arrangement.

What is claimed is:

1. A superconductor circuit comprising a plurality of superconductive electromagnetic coils enclosed within a container maintained at a very low temperature and adapted to be individually energized with an arbitrary value of current, a plurality of superconductor switching elements individually connected with said coils to form a plurality of closed loop current circuits, means connecting said closed loop current circuits in series circuit between two current supply leads emerging from the container and in a manner such that each switching element in its superconductive state will bypass all of the current supplied by said supply leads away from its associated coil, and means for selectively controlling the state of said switching elements.

2. A superconductor circuit as claimed in claim 1 further comprising a source of adjustable current externally connected to said two current leads.

3. A superconductor circuit as claimed in claim 1 wherein said control means comprises a plurality of control coils individually located adjacent individual ones of said switching elements within the container and means external of the container for selectively supplying control currents to said control coils whereby a selected control coil applies a magnetic field to the associated switching element of a magnitude to drive said element into its normal state.

4. A circuit as claimed in claim 1 characterized in that one of the two current leads is formed by an electrically conductive part of a device, part of which is formed by this arrangement.

5. A circuit as claimed in claim 1 characterized in that the superconductive switch is a wireless switch.

6. A circuit as claimed in claim 1 characterized in that the superconductive, electromagnetic coils form part of an electron-optical device.

7. A circuit as claimed in claim 1 characterized in that the superconductive, electromagnetic coils form part of an accelerator for charged elementary particles.

8. A circuit as claimed in claim 1 characterized in that the superconductive, electro-magnetic coils are formed by a superconductive memory elements of a computer.

9. A superconductor circuit comprising a plurality of superconductor coils adapted to carry currents of different magnitudes, a plurality of superconductor switching elements each with first and second terminals, a container adapted to be maintained at a low superconductive temperature and housing said coils and switching elements, first and second current supply leads arranged to supply current from an exterior point to the elements within the container, means connecting one end of a first coil to the first current supply lead and the other end to one end of a second coil, means connecting a first one of said switching elements in parallel with said first coil thereby to form a closed loop current circuit for said first coil, means connecting a second one of said switching elements in parallel with said second coil thereby to form a closed loop cirrent circuit for said second coil, means connecting the other end of said second coil to the second current supply lead whereby said closed loop circuits are connected in series circuit between the first and second current supply leads, a plurality of control conductors located within the container in the vicinity of individual ones of said switching elements, and means external to the container for selectively supplying control currents to said control conductors to produce a persistent current in one or more of said closed loop circuits.

10. A superconductor circuit as claimed in claim 9 wherein the first terminal of the first superconductor switching element is connected directly to said first current supply lead and to said one end of the first coil and the second terminal of said first superconductor switching element is connected directly to the other end of said first coil and to said one end of the second coil.

11. A superconductor circuit as claimed in claim 9 further comprising external means coupled to said current supply leads for adjusting the magnitude of the persistent current in a given coil independently of the control conductor current by varying the magnitude of the supply current in said supply leads at a time when the switching element associated with said given coil is driven into its normal state by its associated control conductor.

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