United States Patent

[11] **3,602,854**

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Tokyo, Japan
[32] Priority **Nov. 4, 1968, Nov. 11, 1968, May 2, 1969**
[33] **Japan**
[31] **43/79968, 43/81854 and 44/33619**

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[54] **FLUX PUMP**
9 Claims, 18 Drawing Figs.

[52] **U.S. Cl.** **335/216,** 317/123
[51] **Int. Cl.** **H01f 7/22**
[50] **Field of Search** 335/216; 317/123

[56] **References Cited**
UNITED STATES PATENTS

3,277,322	10/1966	Berlincourt	317/123 X
3,320,522	5/1967	Arnold	335/216 X
3,336,509	8/1967	Atherton	317/123

Primary Examiner—G. Harris
Attorney—Craig, Antonelli, Stewart and Hill

ABSTRACT: A plurality of discs each made of a superconducting material and having keyhole-shaped slots formed peripherally therein are mounted on a rotary shaft in such a manner that the surfaces of the discs are parallel to each other. A fixed loop member having a pair of superconductive loops connected with each other by two lead wires is interposed between adjacent ones of the discs for the linkage of an external magnetic flux with the loops which is imposed vertically on the discs and passing through the slots, and a large capacity superconductive magnet is connected to the lead wires for pumping the flux thereinto. In the above construction, when the discs are rotated, the superconductive state of the superconductive loops is broken alternately by the flux passing through the slots and thereby the flux is cumulatively transferred into the magnet.

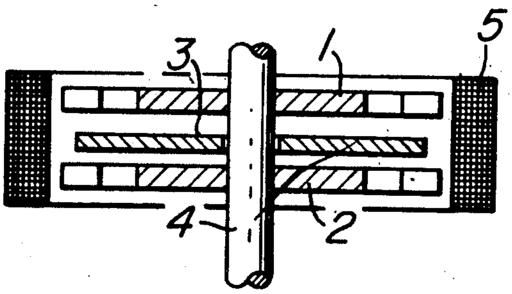

FIG. 1

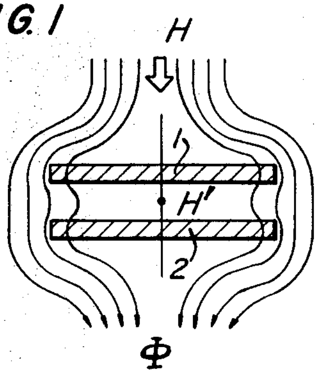

FIG. 2

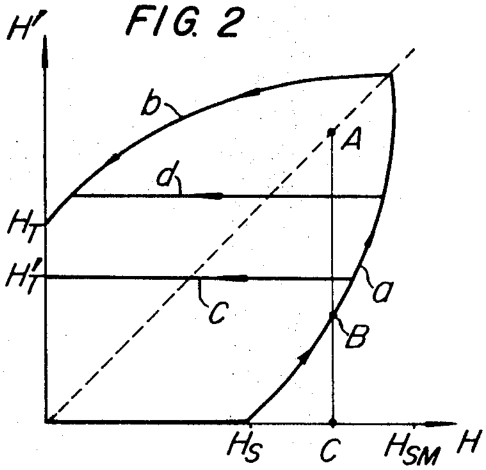

FIG. 3a

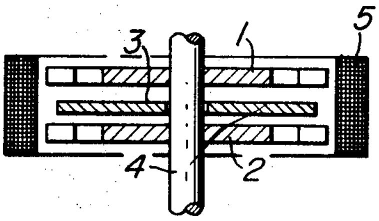

FIG. 3b

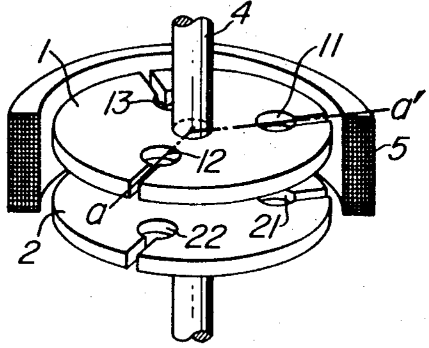

FIG. 3c

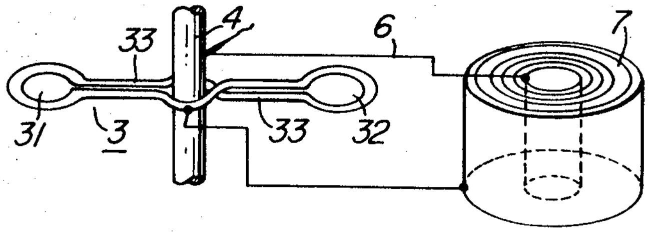

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FIG. 4a

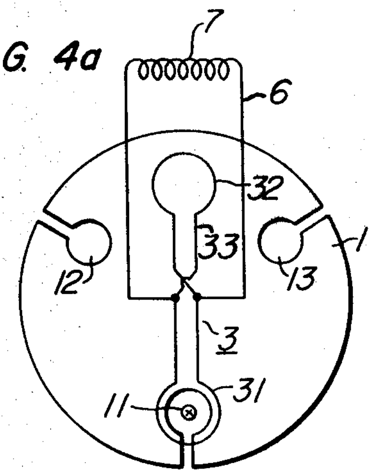

FIG. 4b

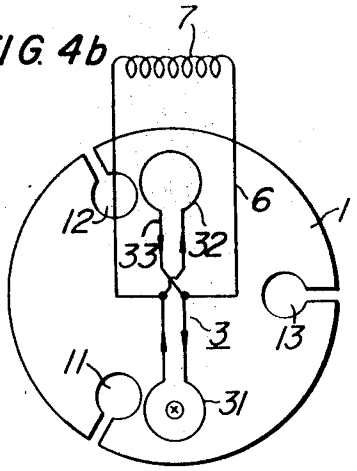

FIG. 4c

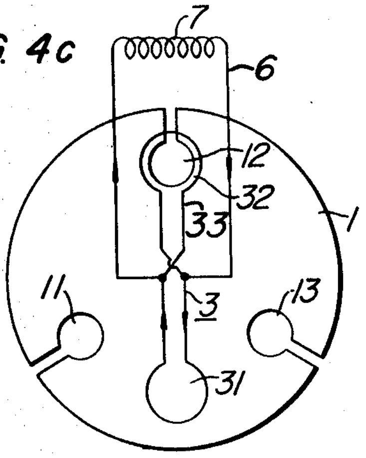

FIG. 4d

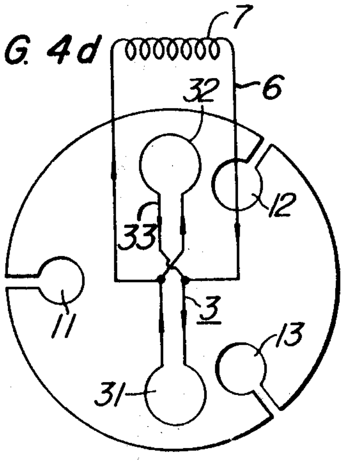

FIG. 5

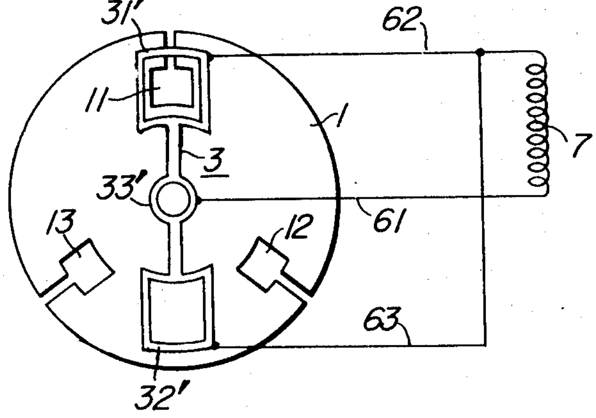

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FIG. 6a

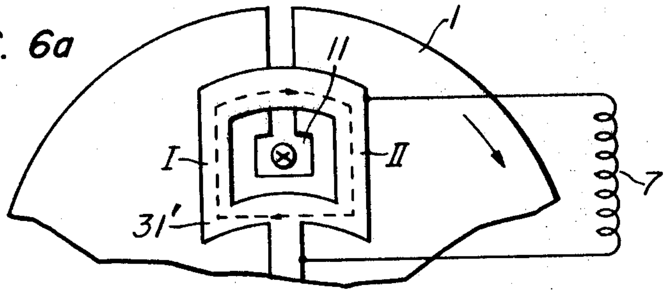

FIG. 6b

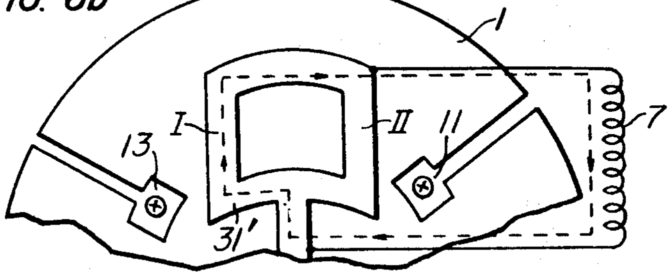

FIG. 6c

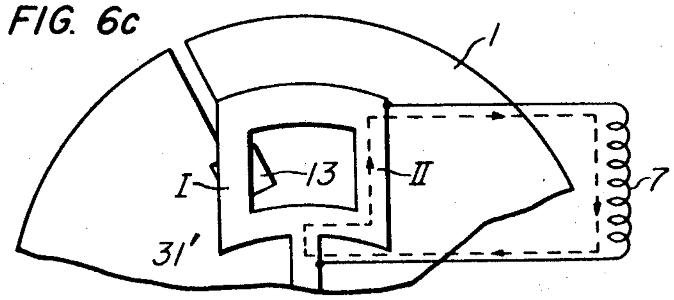

FIG. 7a

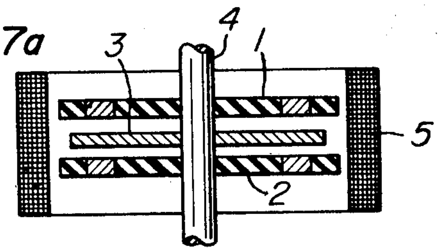

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FIG. 7a

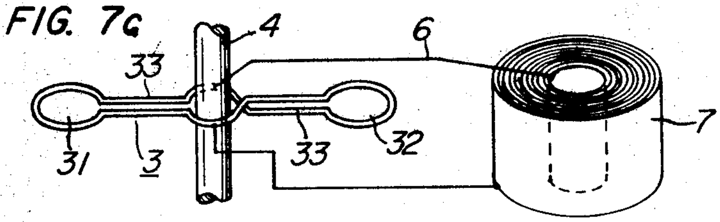


FIG. 8

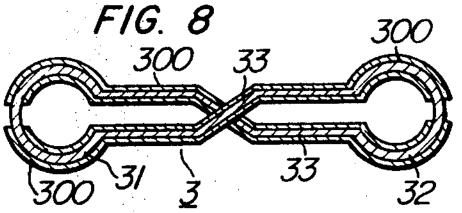


FIG. 7b

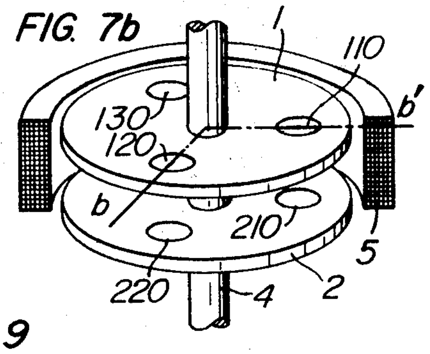
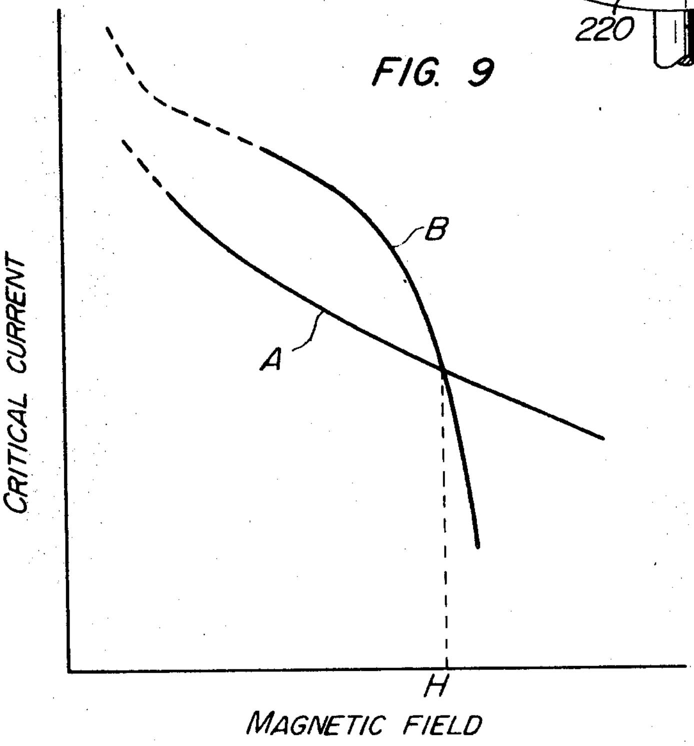


FIG. 9



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FLUX PUMP

The present invention relates to a rotary flux pump and more particularly to a flux pump which is so designed that at least two superconductor discs arranged in parallel relationship to each other and each having notches formed therein are rotated to generate an alternating magnetic field therebetween and the flux is cumulatively accumulated by taking advantage of the field change.

It is well known that a superconductive magnet having a large capacity is used as a DC magnet, for example, for MHD power generation or the like, and a flux pump is normally used for exciting superconductive magnets of such large capacity. The flux pump of the type described is so constructed that the energy generated by a small capacity magnet is cumulatively transferred to a large capacity magnet by a suitable switching mechanism, thereby exciting the large capacity magnet. However, conventional flux pumps unexceptionally had the drawback of being incapable of exciting a large capacity magnet in a short period of time and if an attempt is made to meet this requirement, the apparatus becomes large in size and hence the heat loss become large.

It is, therefore, an object of the present invention to provide a flux pump which is capable of exciting a large capacity magnet in a short period of time, more particularly a flux pump which is capable of generating a magnetic field, for instance, of about 50 kg. in a period of 20 seconds.

Another object of the present invention is to provide a flux pump in which, in order to excite a large capacity magnet, the component parts are made of superconducting materials and used in a superconductive state by maintaining them at a low temperature by the use of liquid helium or the like, whereby the heat loss is minimized and the operation efficiency is enhanced.

It is still another object of the present invention to provide a rotary flux pump having a simpler switching mechanism than that used in the conventional ones, wherein the magnetic flux generated by a superconductive magnet is switched by rotary discs made of a superconducting material.

The other objects, features and advantages of the present invention will be apparent from the following detailed description when read in conjunction with the accompanying drawings, in which:

FIG. 1 is a schematic view for explaining the principle upon which the present invention is based;

FIG. 2 is a diagram showing the characteristic curve of the magnetic field H' between the discs of FIG. 1, relative to the external magnetic field H;

FIG. 3*a* is a cross-sectional view taken along the line *a—a'* in FIG. 3*b;*

FIG. 3*b* is a perspective view showing the practical construction of an embodiment of the present invention;

FIG. 3*c* is a schematic view of a superconductive connecting loop and a magnet to be pumped with flux, which are to be interposed between the discs 1 and 2 shown in FIG. 3*b;*

FIGS. 4*a* to 4*d* are views for explaining the operation of the device shown in FIGS. 3*a* to 3*c;*

FIG. 5 is a schematic view for explaining another construction according to the present invention;

FIGS. 6*a* to 6*c* are schematic views for explaining the operation of the device shown in FIG. 5;

FIG. 7*a* is a cross-sectional view taken along the line *b—b'* in FIG. 7*b;*

FIG. 7*b* is a perspective view schematically showing another embodiment of the present invention;

FIG. 7*c* is a schematic view of a loop member and a magnet to be pumped with flux, which are to be interposed between the discs shown in FIG. 7*b;*

FIG. 8 is a view showing the specific construction of the loop member; and

FIG. 9 is a diagram showing the magnetic field vs. critical current characteristic of a superconducting material which forms a connecting loop.

First of all, the principle behind the present invention will be explained with reference to FIGS. 1 and 2.

Referring to FIG. 1, numerals 1 and 2 designate discs which are held in parallel relationship to each other by means not shown and which are made of an inhomogeneous hard superconducting material. As the inhomogeneous hard superconducting material, Nb-Zr-Ti alloys, sintered Nb_3Sn and $Nb_3(Al_{0.8}, Ge_{0.2})$ may be named for example. Now, when an external magnetic field H is impressed perpendicularly on the disc surface while maintaining the discs at a temperature below the transition temperature *Tc* of the material of which said discs are made, and the intensity of the external magnetic field is changed, the magnetic field H' on the axis and at the middle point between said discs varies as represented by the curve of FIG. 2. As will be seen in FIG. 2, when the intensity of the external magnetic field H is progressively increased from 0, the intensity of the magnetic field H' in the interspace between the discs remains substantially 0 until the intensity of the external magnetic field H reaches a certain value H_s, and the magnetic field H' appears only when the intensity of said external magnetic field H exceeds the value H_s. Namely, the interspace between the discs is substantially completely shielded magnetically for the period when the intensity of the external magnetic field H is smaller than the value H_s. Such value H_s will hereinafter be referred to as the shielding magnetic field. When the external magnetic field H is further increased from H_s, H' also increases along the curve *a*. Namely, the flux of the magnetic field H partially penetrates the discs 1 and 2, and the entire external magnetic field H penetrates the discs 1 and 2 at the intersection of the curve *a* with a straight dotted line representing $H'=H$ (at the point where $H=H_{SM}$ in the diagram). Namely, the discs 1 and 2 return to a normal conductive state at the external magnetic field H_{SM}. Then, when the external magnetic field H is progressively decreased from H_{SM}, H' also decreases along the curve *b* but does not become 0 even when H becomes 0. This means that a magnetic field H_T is trapped between the discs 1 and 2. This H_T will hereinafter be referred to as the trapped magnetic field. Further, when the temperature of the discs 1 and 2 is elevated by a heater to bring them into the normal conductive state, after making the external magnetic field H larger than the shielding magnetic field H_S, and thereafter the external magnetic field H is returned to 0, the field H' varies along the lines *c* and *d*. Namely, in this case also, a magnetic field H_T' is trapped between the discs 1 and 2 when H' varies along the line *c*, and a magnetic field H_T is trapped when H' varies along the line *d*.

Here, the values of H_S and H_T, and the configuration of the H'—H curve, are variable depending upon the type of the hard superconducting material used, the microstructure (lattice defects, such as dislocation and precipitation) of said material, the geometrical conditions of the parallel discs and cooling conditions.

Any superconducting material more or less has a trapped magnetic field H_T and a shielding magnetic field H_S as shown in FIG. 2, but an inhomogeneous hard superconducting material is particularly suitable for use in the present invention because the values of H_T and H_S are large.

According to the present invention the flux is alternated by making use of the magnetic shielding and trapping characteristics of a superconducting material and the resultant alternating flux is pumped. For convenience in explanation, however, the invention will be described hereunder with reference to the case of utilizing the magnetic shielding characteristic of the superconducting material.

With reference to FIGS. 3*a*, 3*b* and 3*c*, numerals 1 and 2 designate discs made of an inhomogeneous hard superconducting material consisting of a Nb-Zr-Ti ternary alloy. Although only two discs are shown, it is a common practice that more than two discs are mounted on a single rotary shaft in juxtaposed relationship. Furthermore, the hard superconducting material is not restricted only to the alloy mentioned above and sintered Nb_3Sn may be used for example. The discs 1 and 2 respectively have three keyhole-shaped slots 11, 12, 13 and **21, 22, 23** (**23** not shown) formed therein peripherally thereof at equal angular distances with respect to the axes thereof. The number of such slots is optional, so is the shape of the same. However, it is essential that the slot is open to the outside of the disc through a breakage formed in said disc and not completely closed by the superconducting material. This is because, if the slot is completely closed peripherally by the superconducting material, the flux will not penetrate the slot even when an external magnetic field is imposed on the disc which is held in the superconductive state. Numeral **4** designates a rotary shaft on which the discs **1** and **2** are mounted in parallel relationship to each other. The discs **1** and **2** are rotated at a predetermined speed about the axis of said rotary shaft **4**, but driving means for said rotary shaft is not shown. Between the discs **1** and **2** is fixedly mounted a loop member **3**. The loop member **3** has two loops **31** and **32** which are made of a superconducting material and connected with each other by lead wires **33** which are also made of superconducting material. Namely, the loops **31** and **32** and the lead wires **33** form one superconductive closed loop. However, as will become apparent as the description proceeds, it is essential that the critical magnetic field of the loops **31** and **32** be smaller than that of the discs **1** and **2**. The number of the loops **31** and **32** to be connected together may be larger than two. The loop member **3** is arranged in such a manner that the loops **31** and **32** are located at positions between the slots in the discs **1** and **2**. Therefore, the flux passing through the slot of the disc **1** links the corresponding loop and then goes out through the slot of the disc **2**. In order for major portions of the fluxes, passing through the slots of discs **1** and **2** to link the loops **31** and **32**, respectively, it is preferable to reduce the distance between the discs and to make the diameter of the loops slightly larger than the diameter of the slots. Numeral **7** designates a coil for constituting a superconductive magnet of large capacity, and the terminals of said coil and the midpoints of the lead wires **33** are connected with each other by lead wires **6** which are also made of a superconducting material. The system comprising the discs **1** and **2** and the loop member **3** is encircled by an annular superconductive magnet **5** arranged coaxially with the rotary shaft **4**. The magnetic field perpendicular to the surface of the discs **1** and **2** is formed by this annular superconductive magnet **5**.

The assembly of the above-described members **1** to **7** is immersed in liquid helium and maintained in a superconductive state. The cooling device used is not shown in FIGS. 3*a* and 3*b*.

The device shown in FIGS. 3*a* and 3*b* operates in the following manner: First of all, the superconductive magnet **5** is excited to generate a magnetic field perpendicular to the disc surfaces. The intensity of the magnetic field is selected to be on the order of the shielding magnetic field H_S. In this case, about the same magnetic field is present at that portion of the interspace between the discs **1** and **2** where the slots in said respective discs are opposed to each other, but the magnetic field H' at the other portion of the interspace between the discs **1** and **2** is substantially 0 as will be apparent from FIG. **2**. Now, when the discs **1** and **2** are rotated by the driving means, the flux links the loops **31** and **32** of the loop member **3**, fixed between the discs **1** and **2**, alternately and successively pumped into the coil **7** of the large capacity magnet as will be described later. When the external magnetic field H to be impressed perpendicularly on the discs **1** and **2** is selected within the range of $H_S<H<H_{SM}$, it is not completely shielded by the discs **1** and **2**, but is shielded to some extent (because $H'<H$). Therefore, a difference also occurs in this case, between the magnetic field at the portion of the interspace between the discs where the slots are opposed to each other, and the other portion of the interspace. Thus, it will be seen that the magnetic field generated by the superconductive magnet **5** is not necessarily smaller than H_S but may be of a suitable value above H_S.

Now, the process of the flux, linking the loops **31** and **32**, being pumped into the coil **7** of the large capacity superconductive magnet will be described with reference to FIGS. **4***a*, **4***b*, **4***c* and **4***d*.

When the discs **1** and **2** are rotated, the relative position of the slots in said discs and the superconductive loops varies as shown in FIGS. 4*a* to 4*d*.

FIG. 4*a* shows the state wherein the loop **31** of the superconductive loop member **3** and the keyhole-shaped slot **11** are in register with each other. The loop member **3** is made of a material whose critical magnetic field is smaller than the magnetic field present between the slots, as described previously. Therefore, in the state of FIG. 4*a* the superconductivity of the loop member **3** is partially broken, with the result that the magnetic flux extending perpendicularly to the sheet of FIG. 4*a* and passing through the slot **11** links the loop **31**. When the discs are rotated from the position of FIG. 4*a* of the drawing to the position of FIG. 4*b* and the loop **31** is returned to the superconductive state, the flux linking the loop **31** is bound by the loop and trapped therein. Thus a current flows through the loops **31** and **32** in the direction indicated in FIG. 4*b*. This process is called magnetic inhalation. In this case, the magnetic flux Φ trapped within the loop **31** is represented by the formula

$$\Phi=(1-\gamma)HS \qquad (1)$$

Where

γ:the magnetic shielding constant of the discs **1** and **2**, which in case of FIG. **2**, is represented by $\overline{BC}/\overline{AC}$ and which, therefore, is a value approximating 0 when the external magnetic field is smaller than H_S

H:the intensity of external magnetic field

S:the area of the slot.

In this process, the change in the magnetic flux linking the loop **31** is Φ. Therefore, the current flowing through the superconductive loop member **3** consisting of **31**, **33** and **32** is represented by

$$H_f=(\Phi/2L) \qquad (2)$$

where

L:the inductance of the loops **31** or **32**, the inductance of the lead wires being neglected.

The current induced in the loop **31** flows only through the closed circuit of the loop member **3** and does not flow into the large capacity superconductive magnet **7** through the lead wires **6**. This is because, although the loop member **3**, the lead wires **6** and the magnet **7** are in the superconductive state, there is in fact a slight contact resistance between the lead wires **33** and **6**. On the other hand, such contact resistance does not exist in the closed loop member **3** since the component parts thereof are made of the same material.

When the discs are displaced from the position shown in FIG. 4*b* to the position shown in FIG. 4*c*, the superconductive state of the loop **32** is broken at a portion thereof by the magnetic flux passing through the slot **12**. As a result, the current flowing through the superconductive loop member **3** now flows through the closed circuit composed of the loop **31** and the coil **7**. This current I_1 is given by the relation

$$I_1(L+L_0)=\Phi \qquad (3)$$

where L_0 is the inductance of the coil **7** of the large capacity magnet. Thus, the magnetic flux Φ is distributed to the coil **7** of the large capacity superconductive magnet and the loop **31**. The magnetic flux Φ_1 distributed to the coil **7** is represented by

$$\Phi_1=I_1L_0=\frac{L_0}{L+L_0}\Phi \qquad (4)$$

When the superconductive state of the loop **32** is broken upon shifting of the discs to the state of FIG. 4*c*, the flux passing through the slot **12** enters the inside of the loop **32**, and when the discs are shifted to the position of FIG. 4*d*, the superconductive state of the loop is recovered. Thus, the magnetic flux linking the loop **32** is bound within said loop and trapped therein. Namely, magnetic inhalation occurs as described previously. The magnetic flux inhaled is represented by formula (1). When the slot **13** is brought into registration with the superconductive loop **31** upon further rotation of the discs from the position shown in FIG. 4*d*, the relative position of the discs and the loop member becomes the same as that of FIG. 4*a* and the same phenomenon occurs, although in the state of FIG. 4*a* the loop **31** is in register with the slot **11**. When the discs have been placed in the position of FIG. 4*a* from the position 4*d* upon rotating as described above, the superconductive state of the loop **31** is broken and a current flows through the closed circuit composed of the superconductive loop **32** and the coil **7** of the superconductive magnet. Representing this current by I_2, the following relation is established:

$$I_2(L+L_0)=\Phi_1+\Phi=\Phi\left(1+\frac{L_0}{L+L_0}\right) \qquad (5)$$

Therefore, the magnetic flux Φ_2 distributed to the coil **7** is

$$\Phi_2=I_2L_0=\Phi\left\{\frac{L_0}{L+L_0}+\left(\frac{L_0}{L+L_0}\right)^2\right\}=\Phi(\lambda+\lambda^2) \qquad (6)$$

where $\lambda=(L_0/L+L_0)$

The above-described operation is repeated, whereby the magnetic flux is gradually pumped into the coil **7**. For instance, when the operation is repeated n times, the flux Φ_n pumped into the coil **7** is

$$\Phi_n=\frac{\lambda-\lambda^{n+1}}{1-\lambda} \qquad (7)$$

and when $n\rightarrow\infty$

$$\Phi_\infty=\Phi\frac{\lambda}{1-\lambda}=\Phi\frac{L_0}{L} \qquad (8)$$

Normally, L_0 is extremely larger than L. Therefore, the value of Φ_∞ becomes greatly large.

Now, the result of the experiment conducted with the device of FIGS. 3*a* to 3*c* will be explained hereunder:

The discs **1** and **2** were made of sintered Nb_3Sn. The sintered Nb_3Sn was compressed under a pressure of 1 ton/cm.^{2} and subjected to a heat treatment at 1000° C. for 10 hours. The loop member **3** was made of Nb-10Zr alloy. The critical magnetic field of the sintered Nb_3Sn is about 230 kg. and that of the Nb-10Zr alloy is about 40 kg. The coil **7** of the superconductive magnet was made of Nb-40Zr-10Ti alloy and the lead wires **6** were also made of the same material. The critical magnetic field of this material is 105 kg. The magnetic field generated by the magnet **5** was 50 kg. The diameter of the keyhole-shaped slots formed in the discs **1** and **2** was 0.5 cm.; the inductance L of each of the loops **31** and **32** was 1μH; and the inductance of L_0 of the large capacity superconductive magnet coil **7** was 225 mh. With the construction described, when the discs **1** and **2** were rotated at 3000 r.p.m., the magnetic field in the center of the large capacity superconductive magnet **7** was 50 kg. Namely, a superconductive magnet of large capacity, capable of generating a magnetic field of about the same intensity as that generated by a magnet of small capacity, can be realized by the use of a superconductive magnet of small capacity.

Although in the embodiment described above, the loop member **3** is so constructed that the loops **31** and **32** are connected with each other so as to form a single closed loop as a whole, it is to be understood that these loops may be connected so as to form a closed circuit individually.

An example thereof is shown in FIG. **5**. In FIG. **5**, there are shown the disc **1** and the loop member **3** only, but it should be understood that the device is actually constructed in the same way as the one shown in FIGS. 3*a* and 3*b*.

As will be apparent from FIG. **5**, the superconductive loop member **3** fixed between the discs **1** and **2** comprises superconductive closed circuits **31′** and **32′** which individually form a closed loop and which are connected with each other by a connecting member **33′**. The connecting member **33′** and the respective closed circuits **31′** and **32′** are connected with the large capacity superconductive coil magnet **7** by superconductive lead wires **61**, **62** and **63** respectively.

The operation of the device of FIG. **5**, constructed as described above, will be explained with reference to FIGS. **6***a*, **6***b* and **6***c*. Although in these Figures the disc **1** and the loop member **3** are partially shown, it should be understood that the keyhole-shaped slots are formed in the discs **1** and **2** in opposed relation. Further, the positional relation between the slots not shown in the Figures and the superconductive loop member is omitted, as will readily be understood.

First of all, when the slot **11** of the disc **1** is in register with the closed loop **31′**, as shown in FIG. **6***a*, and the magnetic flux passes through the slot perpendicularly to the sheet of the drawings, a circulating current flows through the closed loop **31′** as indicated by the dotted line arrow. Now, when the slot **11** is located in a position opposite to a portion II of the closed loop **31′** upon rotation of the discs in the direction of the solid line arrow, the superconductive state of the loop is broken at said portion II, so that the current carried in the closed loop **31′** flows into the superconductive coil **7**. Then, the slot **11** is located in a position shown in FIG. **6***b*, whereupon the portion II of the closed loop **31′** is immediately returned to the superconductive state but the current continues to flow in the direction of the dotted line due to inertia. In this case, the slot **13** is located in a position shown in FIG. **6***b*, but when it is brought to a position opposite to a portion I of the closed loop **31′**, as shown in FIG. **6***c*, upon further rotation of the discs, the superconducting property of the loop is lost at said portion I and the current flows through the portion II of the closed loop **31′** as indicated by the dotted line. Then, the slot **13** is brought into registration with the closed loop **31′**, whereupon the portion I quickly returns to the superconductive state, and the discs and the loop member are placed in the same positional relation as shown in FIG. **6***a*.

By repeating the above-described operation, the current flowing through the large capacity superconductive magnet coil **7** becomes progressively larger. In other words, the flux is gradually accumulated in the coil **7**.

Although the foregoing description has been given with reference to a device wherein one loop member **3** is fixedly mounted between two discs **1** and **2**, in an actual device a large number of discs are mounted on the rotary shaft, with the loop member interposed therebetween respectively, and these loop members are connected in parallel to the superconductive coil **7**. By so doing, more flux can be pumped into the coil on each revolution of the disc system. To increase the number of slots formed in each disc is also effective in pumping more flux in a shorter period of time.

The devices shown in FIGS. 3*a* and 3*b* and FIG. **5** are all those which take advantage of the magnetic shielding property of an inhomogeneous hard superconducting material. However, it is to be noted that similar flux pumps can also be obtained by making use of the magnetic trapping property of the same material.

The practical construction of such a device is exemplified in FIGS. 7*a* to 7*c*.

In the device shown in FIGS. 7*a* to 7*c*, the discs **1** and **2** are made of an electrically insulating material such as Bakelite for example. Each disc is provided with three circular holes peripherally thereof at an equal angular distance with respect to the axis of rotation, and three magnetic poles **110**, **120** and **130** or **210**, **220** and **230** (not shown) are fitted in said respective holes, said magnetic poles being made of a superconducting material. Between the discs **1** and **2** is fixedly mounted the loop member **3** which, as shown in FIG. 7*c*, is composed of the superconductive loops **31** and **32** connected with each other by the lead wires **33** made of superconducting material. The construction of the other portions are the same as in FIGS. 3*a* and 3*b* and, therefore, will not be described herein.

When the superconductive magnet coil **5** is excited to generate an external magnetic field and said magnetic field is increased gradually, the portion other than the magnetic poles of the discs **1** and **2** permits the magnetic flux to permeate therethrough, but the portions of the magnetic poles shield the magnetic field, when the magnetic field is below H_S, as will be apparent from FIG. 2. However, when the external magnetic field is intensified to the level of H_{SM} shown in FIG. 2 and then decreased to 0, the magnetic field of H_T, shown in FIG. 2, is present between the magnetic poles **110** and **210**, the magnetic poles **120** and **220**, and the magnetic poles **130** and **230**, in spite of the external magnetic field being 0. After having the magnetic field trapped between the opposed magnetic poles in the manner described, the discs **1** and **2** are rotated, whereupon a magnetic field change occurs between the discs, which is exactly the same as in the case when the external magnetic field is imposed on the discs **1** and **2** having the slots therein as shown in FIG. 3. Therefore, the superconductive state of the loops **31** and **32** of the loop member **3** is broken alternately, as described previously, and the flux is pumped into the large capacity superconductive magnet **7** according to formulas (1) to (8).

In the flux pumps described and illustrated hereinabove, the superconductive state of the loops **31** and **32** of the loop member **3**, interposed between the discs **1** and **2**, is partially broken alternately by the magnetic field passing through the slots or trapped between the magnetic poles fitted in the discs **1** and **2**. Now, referring to the state of the superconductive property of the loops **31** and **32** being partially broken as "off" operation and to the state of the same being recovered as "on" operation, the loops **31** and **32** in the devices of FIGS. 3 and 7 respectively repeat the on-off operations three times in one revolution of the discs **1** and **2**.

In these loop members **3**, the loops **31** and **32** and the lead wires **33** interconnecting said loops are made of the same material, e.g. of Nb-10Zr alloy, and hence the critical magnetic field is the same at any portion of the loop member. However, the lead wires **33** do not perform the on-off operation and must always be maintained in the superconductive state. Therefore, it is preferable that the critical magnetic field of the portions of the loop member **3** which link the magnetic field (that is, the loops **31** and **32**) is small to assure the on-off operation, and that of the lead wires **33** is large so that the superconductive state thereof may not be broken by the leading magnetic field.

In order to fulfill such requirement, the superconductive loop member **3** may be constructed as shown in FIG. **8**.

On the premise that the magnetic field passing through the slots shown in FIG. 3 or trapped between the magnetic poles shown in FIG. 7 is 50 kg., the loops **31** and **32** and the lead wires **33** interconnecting said loops are produced in a shape as shown in FIG. **8**, using Nb-10Zi alloy (the critical magnetic field being 40 kg.) or Nb-3Zi for example. After cleaning the surface of the loop member with an acid, the loop member is immersed in molten Sn or Ga, with the loops **31** and **32** being partially masked, whereby a Sn or layer or Ga layer is formed on the lead wire portions in a uniform thickness. Thereafter, the loop member is heated at 900°–1200° C. in vacuum or in an inert atmosphere, thereby forming a compound layer **300** of Nb_3Sn or Nb_3Ga on the surface of said Nb-base superconductive alloy. The critical magnetic field of the Nb_3Sn layer is about 230 kg., which is considerably greater than the critical magnetic field of Nb-10Zi or Nb-3Zi alloy.

FIG. **9** shows the value of the critical current of Nb-10Zi alloy (the curve B) and that of Nb_3Sn compound (the curve A), relative to the magnitude of the magnetic field. As seen, the critical current of the Nb-10Zi alloy declines rapidly and that of the Nb_3Sn compound declines slowly, as the magnetic field is intensified. It will, therefore, be seen that the superconductive state of the Nb-10Zi is easily broken and that of the Nb_3Sn is hardly broken, under a magnetic field which is larger than the magnetic field H_{nb} at the intersection of curves A and B. Namely, the loop member satisfies the aforesaid requirements.

Such loop member may also be produced by the following method: Namely, a bare loop member is made of the Nb-base alloy and after partially masking the loops **31** and **32** with a polymer, the Sn layer or Ga layer is formed on the unmasked portion by plating or vacuum evaporation. Then, the loop member is heated at 900°–1200° C. to form the compound layer on the surface of the Nb-base alloy.

By either method, the loops **31** and **32** of the loop member produced perform a reliable on-off operation and the connecting lead wires **33** thereof maintain their superconductive state regardless of the rotation of the discs.

Although the present invention has been described and illustrated herein with reference to particular embodiments thereof, it is to be understood that the invention is not restricted only to those embodiments but many changes and modifications can be made as desired without deviating from the spirit and scope of the invention.

What is claimed is:

1. A flux pump comprising
at least two discs each made of a superconducting material and having slots formed therein at optional positions in such a manner that a slot in one disc is opposed by a slot in the other disc and each slot is communicating with the outside of the disc through a breakage formed in said disc,
a rotary shaft on which said discs are mounted for rotation therewith,
means for forming a magnetic field perpendicular to the surfaces of said discs,
a fixed superconductive loop member interposed between said discs so that said magnetic flux passing through said slots may link the superconductive loop member,
a superconductive magnet or large capacity for pumping the flux thereinto, and
superconductive lead wires interconnecting the coil of said magnet and said loop member,
the superconductive state of said loop member being broken when each of said slots is brought into registration with said loop member and being recovered when said slot has passed said loop member, repeatedly, whereby the flux is cumulatively transferred into said magnet.

2. A flux pump comprising
at least two discs each made of a superconducting material and having a plurality of keyhole-shaped slots formed therein at an equal angular distance with respect to the axis of the disc in such a manner that a slot in one disc is opposed by a slot in the other disc,
a rotary shaft on which said discs are mounted in parallel relation to each other,
means for forming a magnetic field perpendicular to the surfaces of said discs,
a fixed loop member interposed between said discs and having two superconductive loops connected with each other by two superconductive lead wires in such a manner that said loops and lead wires make a single closed loop as a whole, said loop member being so positioned that the magnetic flux passing through said slots will link said superconductive loops,
a superconductive magnet of large capacity for pumping the flux thereinto, and
superconductive lead wires interconnecting said respective two superconductive lead wires and the terminal ends of the coil of said magnet,
the superconductive state of said superconductive loop being broken alternately, whereby the flux is cumulatively transferred into said large capacity magnet on each time said superconductive state is broken.

3. A flux pump as defined in claim **1**, wherein said loop member has two independent closed loops connected with each other by a unitary superconductive lead wire, and said closed loops and said connecting lead wire are respectively connected to the coil of said large capacity superconductive magnet.

4. A flux pump comprising
at least two discs each made of an electrically insulating material and having holes formed therein at optional positions in such a manner that a hole in one disc is opposed by a hole in the other disc,
a rotary shaft on which said discs are mounted for rotation therewith,

magnetic poles of a superconducting material each fitted in each of said holes for trapping a magnetic field between the opposed ones thereof,

a fixed superconductive loop member interposed between said discs so that the magnetic flux between the opposed ones of said magnetic poles may link the loop member,

a superconductive magnet of large capacity for pumping the flux thereinto, and

superconductive lead wires interconnecting the coil of said magnet and said superconductive loop member, the superconductive state of said loop member being broken when said loop member is located between the opposed magnetic poles and being restored when said loop member has passes said position, repeatedly, whereby the flux is cumulatively transferred into said large capacity magnet.

5. A flux pump as defined in claim **2**, wherein the superconductive loops of said loop member have a diameter larger than the diameter of the slots.

6. A flux pump as defined in claim **1**, wherein the discs are made of an inhomogeneous hard superconducting material.

7. A flux pump as defined in claim **4**, wherein the magnetic poles fitted in the discs are made of an inhomogeneous hard superconducting material.

8. A flux pump as defined in claim **1**, wherein the discs are made of a superconducting material whose critical magnetic field is larger than the external magnetic field imposed vertically on the discs and the superconductive loops are made of a superconducting material whose critical magnetic field is smaller than said external magnetic field.

9. A flux pump as defined in claim **4**, wherein the loop member has two superconductive loops connected with each other by superconductive lead wires, and is made of a Nb-base alloy having a small critical magnetic field, a portion other than said two superconductive loops of said loop member having formed on the surface thereof a layer of superconductive metal compound whose critical magnetic field is larger than that of the Nb-base alloy.