Sept. 3, 1968 D. J. HARRA 3,400,349

U-SHAPED MAGNETIC CIRCUIT INCLUDING THREE PERMANENT MAGNETS SEPARATED BY POLE PIECES

Filed Jan. 14, 1966

FIG. 1

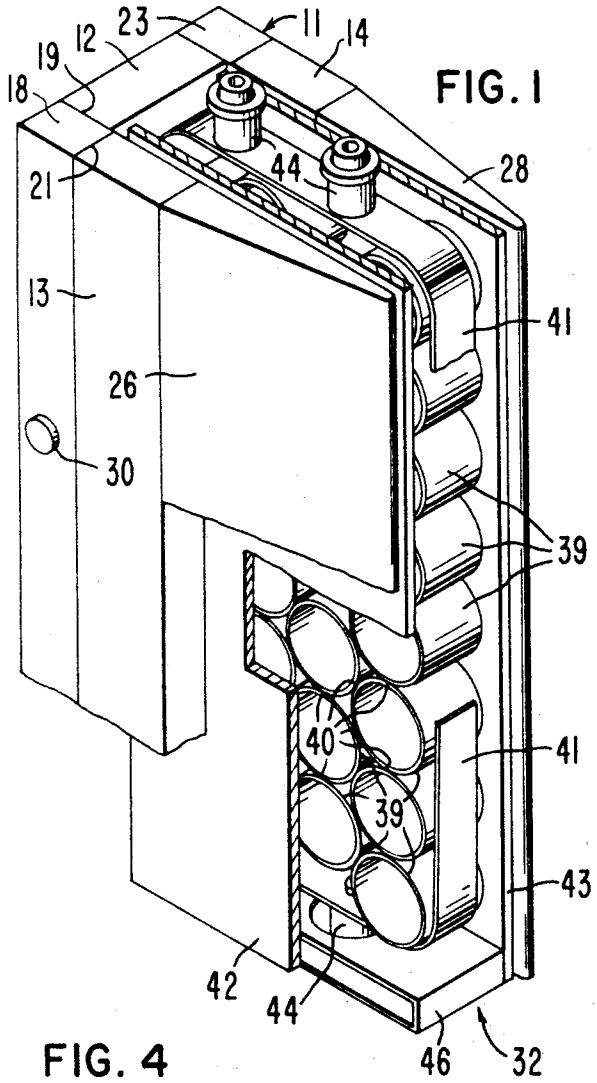


FIG. 2

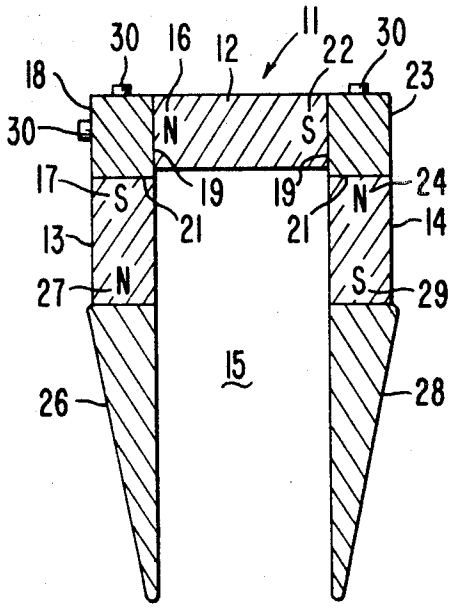


FIG. 3

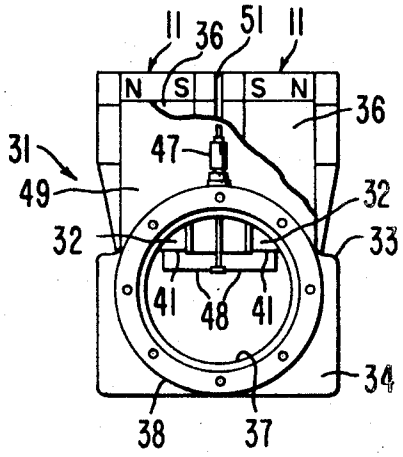
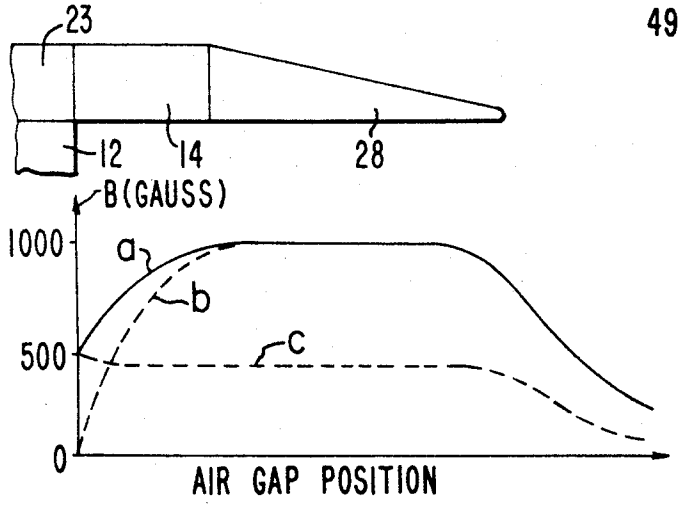


FIG. 4



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U-SHAPED MAGNETIC CIRCUIT INCLUDING THREE PERMANENT MAGNETS SEPARATED BY POLE PIECES

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ABSTRACT OF THE DISCLOSURE

The web or connecting portion of the U is formed by a single bar magnet while each of the arms of the U, perpendicular to the web, includes a bar magnet poled in magnetically aiding relationship to the magnet in the web. A pair of pole pieces magnetically interconnect the web and arms of the U, while another pair of pole pieces at the ends of the arms are tapered to provide a region of uniform flux density between the arms.

The present invention relates generally to U-shaped magnetic circuits. More specifically, it appertains to a magnetic circuit including a plurality of straight permanent magnets separated by pole pieces arranged in a U-shaped configuration which is particularly suited for use with ionic vacuum pumps.

U-shaped magnetic circuits fall into two general categories; those having curved or C-type magnets, and those having bar-type magnets forming straight segments of a rectangular U-shaped magnetic circuit. Both known C-type magnets and rectangular U-shaped magnetic circuits are characterized by various limitations and disadvantgaes. For example, C-type magnets have varying magnetic lengths measured along the direction of magnetization. As is well known, the maximum magnetic field produced in the air gap of a given magnet occurs when the magnet material is operated at the knee of the demagnetization curve. For a given air gap, the point of operation on the demagnetization curve will vary as the magnetic length. Hence, in order for all of the magnetic material to be operating at the knee of the demagnetization curve, the length of the magnetic material along the direction of magnetization must be uniform. Since the C-type magnets have varying magnetic lengths, its operating efficiency, i.e., maximum air gap field intensity throughout a given air gap size for a given magnet size, is inferior in comparison to a magnet characterized by a uniform magnetic length. Furthermore, the manufacturing process of such C-type or other irregularly shaped permanent magnets is exceedingly more complex than the process employed in manufacturing bar-type magnets.

To overcome the problems characterizing the C-type magnets, various U-shaped magnetic circuit configurations employing straight bar-type magnets and pole pieces have been used. One such type employs a single bar magnet having a pole piece extending perpendicularly away from each magnetic pole. Such magnetic circuits are capable of generating air gap magnetic field intensities comparable to the coercive force coefficient of the magnets employed. Hence, such magnetic circuits can optimally produce magnetic fields of, essentially, only a given intensity, therefore being quite inflexible.

To be able to provide magnetic fields of various intensities with a magnetic circuit employing magnets of a given type material while also preventing large flux leakages, magnets are placed close to the air gap, generally, in the arms of the U-shaped configuration. Such a magnetic circuit includes a pole piece having a bar magnet extending perpendicularly away from each end of the pole piece. The latter type is described in the United States Patent 3,182,234 to Paul Meyerer, entitled Permanent Magnet

System for Focusing an Electron Beam in a Travelling Wave Tube, issued May 4, 1965, particularly, the embodiment of FIGS. 1 and 2. However, in each of these cases, the structure of the magnetic circuit required to generate a given air gap magnetic field intensity is large, and in the case of the Meyerer type structure, the profile of the magnetic field intensity established in the air gap is poor, i.e., far from being uniform.

Considerable advantage is therefore to be gained by the provision of a magnetic circuit configuration which overcomes those limitations and disadvantages characterizing the prior art configurations. Other advantages will be realized where a compact and efficient magnetic circuit characterized by a more uniform air gap magnetic field intensity profile is employed to guide the ionizing electrons of a sputter-ion vacuum pump having a cellular anode structure.

The present invention provides an improved U-shaped magnetic circuit configuration which is characterized by being compact and efficient, having a uniform magnetic length, being capable of generating with a given magnetic material an air gap magnetic field of any desired magnitude of intensity, and having an enhanced air gap magnetic field intensity profile by utilizing what is commonly considered lost flux leakage to increase the air gap magnetic field intensity. More specifically, the magnetic circuit configuration of the present invention includes a first straight permanent magnet having a pole piece at each of its poles. Second and third straight permanent magnets are disposed in magnetic potential adding relation with the first magnet. The second magnet is disposed to extend from the pole piece at one pole of the first magnet in a direction perpendicular to the direction of magnetization of the first magnet. Similarly, the third magnet is disposed to extend from the other pole piece in direction perpendicular to the direction of magnetization of the first magnet. Additional pole pieces as required are disposed to extend from and in the same direction as the pole ends of the second and third magnets distal the first magnet to complete the U-shaped magnetic circuit configuration.

By constructing the magnetic circuit with straight magnet sections which are separated by pole pieces so that magnetic paths are straight, the magnetic length of the circuit is made uniform, hence providing a more efficient magnetic circuit. Furthermore, by utilizing a magnet in each arm and at the web section of the U-shaped configuration, an enhanced air gap magnetic field intensity profile is provided as a result of the normally considered lost flux leakage of the web disposed magnet permeating the air gap adding with the field generated by the arm disposed magnets. Also, such magnet placement facilitates varying the magnitude of the air gap magnetic field intensity. Moreover, the three piece magnet structure allows for the construction of a magnetic circuit requiring less material than prior art circuit configurations for a given air gap and magnetic field intensity. Consequently, the efficiency of the magnetic circuit of the present invention will be improved considerably over those of the prior art.

Accordingly, it is an object of the present invention to provide a flexible U-shaped magnetic circuit having an enhanced efficiency characteristic.

More particularly, it is an object of the present invention to provide a U-shaped magnetic circuit having a uniform magnetic length and which generates an enhanced air gap magnetic field intensity profile.

Another object of the present invention is to provide a compact U-shaped magnetic circuit including magnets constructed of a given material whose air gap magnetic field intensity magnitude may be varied as desired.

A further object of the present invention is the provision of a compact U-shaped magnetic circuit configura-

tion particularly suited for use with a modular type sputter-ion vacuum pump.

These and other objects and advantages will become more apparent upon consideration of the following description taken in connection with the accompanying drawing of which

FIG. 1 is a perspective view of an elongated embodiment of the magnetic circuit of the present invention as employed with a cellular anode sputter-ion vacuum pump.

FIG. 2 is a cross-sectional view of the magnetic circuit of FIG. 1.

FIG. 3 is a top view of a two element unit sputter-ion vacuum pump and magnets.

FIG. 4 is a graph representing the air gap magnetic field profile of the magnetic circuit of the present invention as compared with the prior art systems with curve (a) depicting the profile of the magnetic circuit of the present invention, curve (b) depicting the profile of a Meyerer type magnetic circuit, and curve (c) depicting the profile of a U-shaped magnetic circuit employing a single magnet disposed at the web of the U.

Referring to FIGS. 1 and 2 the magnetic circuit **11** comprises three straight magnets **12**, **13** and **14** arranged in a magnetic potential adding U-shaped configuration to define an air gap **15**. The magnets are disposed with magnet **12** defining the web and each of the magnets **13** and **14** defining a segment of one of the arms of the U-shaped configuration. Although the magnets may be of any cross sectional configuration, for sake of simplicity, a rectangular or square configuration is recommended.

To provide a magnetic circuit **11** having a uniform magnetic length, the north pole **16** of magnet **12** is coupled to the south pole **17** of side magnet **13** by a rectangular corner pole piece **18** interposed therebetween. Since pole pieces are constructed of low reluctance material and hence do not provide any magnetization, any pole piece configuration can be employed without affecting the magnetic length characteristics of the magnetic circuit **11**. However, a more efficient magnetic circuit which is considerably easier to manufacture is obtained by employing rectangular block pole pieces whose sides adjacent the poles of the magnets are of the same cross sectional area and geometric configuration. Hence, in the preferred arrangement of the magnetic circuit **11**, perpendicularly extending sides **19** and **21** of pole piece **18** are mated respectively with the north pole **16** of magnet **11** and south pole **17** of magnet **13**. Similarly, the south pole **22** of magnet **12** is coupled by a second rectangular corner pole piece **23** to the north pole **24** of a second side magnet **14**.

In many magnetic circuit applications, e.g., for establishing a magnetic field to trap and guide the ionizing electrons in ionic vacuum pumps, it is desirable to provide a nearly uniform magnetic field profile in the region where the pump elements are disposed in order to minimize the establishment of pressure gradients due to an uneven concentration of electrons. Furthermore, it is desirable to provide such a nearly uniform magnetic field profile over a large area. In such cases, it is contemplated that the magnetic circuit **11** of the present invention will further include additional pole pieces extending from the rectangular pole pieces **18** and **23**. More specifically, a rectangular shaped straight side pole piece **26** is mated to extend from the north pole **27** in the same direction as magnet **13**. Similarly, another rectangular shaped straight side pole piece **28** is mated to extend from and in the same direction as the south pole **29** of magnet **14**. The resultant seven-piece magnetic circuit is assembled by bolts **30** extending between pole pieces on each side of the magnets to threadingly engage the pole piece opposite the pole piece at the bolt head. Other suitable means can be employed to facilitate holding the magnetic circuit structure together, e.g. brackets secured between pole pieces on opposite sides of each magnet or by welding the magnets and pole pieces together.

Any of the permanently magnetic materials can be employed in constructing the magnetic circuit of the present invention. However, for a given size air gap **15** and desired air gap magnetic field intensity, some materials are more desirable than others from the standpoint of magnetic circuit size and efficiency. The selection of magnet materials, generally, is based upon the "peak energy product" characteristic of the material, i.e., the maximum external energy that can be maintained by a unit volume of the material. Furthermore, the "peak energy product" is governed, to some extent, by the residual induction and coercive force characteristics of the material. In the case of the present invention, it has been found particularly advantageous to utilize magnets constructed from materials having a "peak energy product" of at least 5.0×10^6 gauss-oersteds. A particular material having a "peak energy product" falling in this range is heat treated cast alnico, consisting of iron, nickel, aluminum and cobalt, cooled in a magnetic field and whose magnetic orientation is accomplished during heat treatment. Such a material is manufactured by Indiana General Corporation of Valparaiso, Indiana under the designation of Alnico V and has a residual inductance coefficient of 12.5 kilogauss, a coercive force coefficient of 600 oersteds and a "peak energy product" of 5.25×10^6 gauss-oersteds.

For highest possible operating efficiency, i.e., maximum air gap field with the minimum magnet material, the magnet structure is constructed such that the magnet material operates a the knee of the demagnetization curve of the material. For a given magnetization length, air gap size, air gap field, and magnet material, the required magnet structure can be determined by standard techniques. A particular magnetic circuit **11** constructed to provide a 1000 gauss air gap magnetic field for a sputter-type ionic vacuum pump **31** having two pump element units **32** is shown in FIGS. 1–3. As shown therein, the vacuum pump **31** comprises a vacuum envelope **33** having a main chamber **34** and two spaced apart elongated rectangular parallelepiped appendage chambers **36** extending from one side of the main chamber **34** defining three interconnected volumes. The main chamber **34** is communicated to a chamber to be evacuated (not shown) through a port **37** terminating at a flange **38** adapted to be mounted in gas tight relation to the chamber to be evacuated. A flange suitable for such gas tight coupling is the ConFlat® flange described in United States Patent 3,208,758 to Maurice A. Carlson and William R. Wheeler entitled Metal Vacuum Joint, issued Sept. 28, 1965. It is noted that other vacuum pump container configurations may be employed with the magnetic circuit of the present invention. For example, container configurations of only one or more than two appendage chambers **56** could be employed, with appendage chambers **36** extending from any or all sides of main chamber **34**. Also, appendage chamber configurations other than rectangular, that is, for example, circular, could be employed. However, the rectangular appendage chambers **36** facilitate most efficient use of the magnet material since the configuration of the rectangular U-shaped magnetic circuit can be conformed more exactly to that of the appendage chambers **36**.

A pump element unit **32** is inserted in each appendage chamber **36**. A typical pump element unit **32** includes a multi-cell anode comprised of, for example, a plurality of parallelly disposed anode cells **39**, preferably circular cylinders, held together in a rectangular-like bunch by spot welds at their tangent points **40**. Additional support is provided by a strap **41** tightly wrapped about the circumference of the rectangular-like bunch. The anode cells **39** are mounted spaced apart and between cathode plates **42** and **43** with the principal axes of the cells **39** perpendicular thereto. The cathode plates **42** and **43** are constructed from reactive material that is disintegratable upon ion bombardment, e.g., titanium. Alternatively, a coating of such material on a support member could serve as cath-

ode plates. Other multi-cell anode configurations other than that formed by the individual circular cylindrical anode cells **39** could be employed, such as, a rectangular cylindrical cell or any partitioning means defining a plurality of open ended cellular compartments. In all cases, the anode cells **39** must be open enderd cellular compartments mounted with a cathode structure covering the open ends of the cellular structure.

Mounting of the anode cells **39** is accomplished by insulators **44** secured between strap **41** and conductive plate **46** secured to cathode plates **42** and **43**. The required electrostatic field is established by connecting a high voltage source, e.g., 3000 v. DC, (not shown) through a high voltage feedthrough **47** connecting to the anodes **39** by conductors **48** electrically connected to strap **41**.

Each appendage chamber **36** is arranged to be received in nested relation by the air gap **15** of a magnetic circuit structure **11** including elongated rectangular plate magnets and pole pieces. Magnetic circuit **11** may also be mounted within the appendage chamber **36** to receive in its air gap **15** pump element unit **32**. The adjacent magnetic circuits **11** are mounted between platforms **49** (top platform shown) to have like poles proximate each other. With like poles arranged proximate, the magnetic fields generated by each magnetic circuit **11** do not interlink to interfere with or cancel one another in the pump element unit regions. In fact, the leakage flux of each magnetic circuit **11** links with the air gap magnetic field of its adjacent magnetic circuit to produce an enhanced air gap magnetic field. Furthermore, the magnetic fields generated by each magnetic circuit **11** in the space **51** therebetween are in opposition thereby tending to cancel one another therein. The effect of such cancellation is a reduction of the stray magnetic field in the vicinity of the sputter-ion vacuum pump **31**.

A particular magnetic circuit structure constructed to provide a 1000 gauss air gap magnetic field for the sputter-ion vacuum pump **31** had the following specifications. The overall dimensions of magnetic circuit **11** measured 4.50 inches wide, 7.375 inches long, 14.55 inches high, and defined an air gap **15** of 2.5 inches wide by 6.25 inches long. Magnet **12** measured 2.5" x 1.126" x 14.55". Each corner pole piece **18** and **23** measured 1.0" x 1.25" x 14.55". Side magnets **13** and **14** measured 1.0" x 1.875" x 14.55". The side pole pieces **26** and **28** measured 4.25 inches long by 14.55 inches high. More efficient use of the side pole pieces **26** and **28** was obtained by tapering the pole pieces from a 1.0 inch maximum width proximate the side magnets to a 5/16 inch width at their extremities. The magnets **12**, **13** and **14** were constructed from the hereinbefore described alnico material. The pole pieces **18**, **23**, **26** and **28** were constructed from soft iron or low reluctance mild steel. The magnitude of the air gap magnet field can be varied by varying the length of magnets **12**, **13** and **14**.

Referring to curve (a) of FIGURE 4, the air gap magnet field intensity profile of the above identified magnetic circuit **11** taken in the direction of the extending arms of the U-shaped configuration along the center line of air gap **15** was found to be 500 gauss along the surface of magnet **12** facing air gap **15**. The air gap magnetic field intensity increased to 1000 gauss at the junction of side pole pieces **26** and **28** and side magnets **13** and **14**. The air gap magnetic field intensity remained substantially at 1000 gauss in the air gap region between the pole pieces **26** and **28** and decreased towards zero in the region beyond the air gap **15**.

Curve (b) of FIGURE 4 depicts the air gap magnetic field intensity of a magnetic circuit of the type described in the hereinbefore identified Meyerer's Patent 3,182,234. As shown by the curve, the air gap magnetic field intensity goes to zero at the web of the U-shaped configuration. This is because the magnetic potential along the surface of the pole piece located at the web of Meyerer's magnetic circuit is zero. Hence, it is seen that the air gap magnetic field intensity profile of the magnetic circuit of the present invention is considerably enhanced over that of Meyerer's. Furthermore, for a given maximum air gap magnetic field intensity, a Meyerer's type magnetic circuit configuration would be much larger than one constructed in accordance with the present invention. This is seen when it is considered that to generate a magnetic field of a given intensity, a given length of magnetization is required. Hence, to generate a 1000 gauss magnet field, the length of the side magnets in Meyerer's magnetic circuit would be longer than those of the magnetic circuit of the present invention by one-half the length of the web section of the U-shaped configuration.

Curve (c) of FIG. 4 depicts the air gap magnetic field intensity profile of a U-shaped magnetic circuit configuration having a single magnet disposed at the web of the U and having the same overall dimensions as the magnetic circuit configuration of the present invention. Although the air gap magnetic field profile is improved, it is seen that the intensity is only one-half that of the magnetic circuit of the present invention. To generate a magnetic field intensity comparable to that generated by the magnetic circuit of the present invention, a considerably larger single magnet type magnetic circuit structure would be required employing a permanent magnet constructed of material whose coercive force coefficient at least equaled the desired air gap magnetic field.

As noted hereinbefore, many advantages accrue to the magnetic circuit of the present invention as a result of its compactness, increased efficiency, and enhanced air gap magnetic field intensity profile. Most importantly is the ability to construct a more compact and efficient sputter-ion vacuum pump.

While the present invention has been hereinbefore described with respect to a single embodiment, many modifications and variations are possible within the scope of the invention. For example, a U-shaped magnetic circuit configuration of more than three magnets and four pole pieces could be constructed by adding additional pole pieces and magnets in alternation in each leg of the U-shaped configuration. Also, more than one magnet could be positioned in the web section of the U-shaped configuration. Furthermore, the pole pieces could be curved sections instead of straight since the magnetic length is unaffected.

Therefore, the scope of the magnetic circuit of the present invention is not intended to be limited except by the terms of the following claims.

What is claimed is:

1. An improved U-shaped magnetic circuit comprising first, second and third straight permanent magnets arranged in a generally U-shaped magnetic potential adding configuration with said first magnet disposed at its web and said second and third magnets at its arms, and first and second pole pieces, said first pole piece secured at the north pole of said first magnet, said second pole piece secured at the south pole of said first magnet, said second magnet secured at said first pole piece with its south pole adjacent thereto, said third magnet secured at said second pole piece with its north pole adjacent thereto.

2. The magnetic circuit according to claim **1** further comprising a first straight pole piece secured at the north pole of said second magnet to extend therefrom in the same direction as said second magnet, and a second straight pole piece secured at the south pole of said third magnet to extend therefrom in the same direction as said third magnet.

3. The magnetic circuit according to claim **2** wherein said pole pieces and magnets are rectangular blocks.

4. The magnetic circuit according to claim **3** wherein said first and second straight pole pieces each have a side which is tapered from a large end to small end thereof, the tapered side of each pole piece defining a surface facing away from the other straight pole piece with the large end of said first straight pole piece proximate said second

magnet and the large end of said second straight pole piece proximate said third magnet.

5. The magnetic circuit according to claim 1 wherein said magnets are constructed from materials having a peak energy product of at least 5.00×10^6 gauss-oersteds.

6. The magnet circuit according to claim 5 wherein said magnets are constructed from alnico having a residual induction coefficient of 12.5 kilogauss, a coercive force coefficient of 600 oersteds and a peak energy product of 5.25×10^6 gauss-oersteds.

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