

[54] **SUPERCONDUCTING CAVITY
RESONATOR**

[75] Inventor: **Hans Martens**, Erlangen, Germany

[73] Assignee: **Siemens Aktiengesellschaft**,
Munchen, Germany

[22] Filed: **Dec. 11, 1972**

[21] Appl. No.: **313,998**

[30] **Foreign Application Priority Data**

Dec. 24, 1971 Germany..... 2164529

[52] U.S. Cl..... **333/83 R, 333/99 R, 333/99 S**

[51] Int. Cl..... **H01p 1/00, H01p 7/06**

[58] Field of Search... **333/99 S, 83 R, 98 P, 98 BE,**
333/99 R, 98 R; 324/58 C, 58.5 C; 250/250

[56] **References Cited**

UNITED STATES PATENTS

3,348,135 10/1967 Howgate 324/58.5 C

3,748,421 7/1973 Peterson 219/10.55 R

OTHER PUBLICATIONS

Schwettman et al., "The Application of Superconductivity To Electron Linear Accelerators," International Advances in Cryogenic Eng., Proc. of the 1964 Cryogenic Eng. Conf. TP480A3(V10Pt2) 1964, pp. 88, 92.

Primary Examiner—James W. Lawrence

Assistant Examiner—Wm. H. Punter

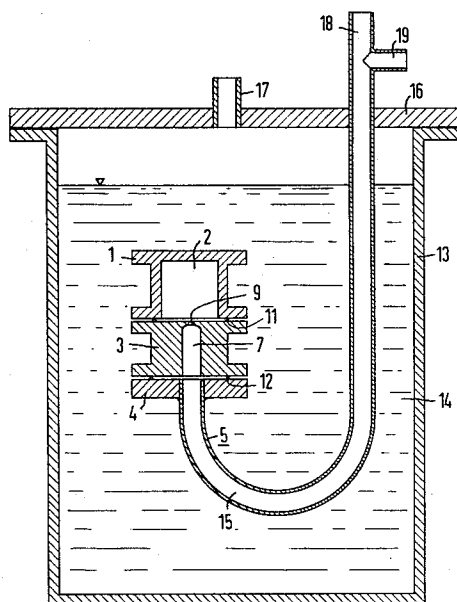
Attorney, Agent, or Firm—Kenyon & Kenyon Reilly
Carr & Chapin

[57]

ABSTRACT

In a superconducting cavity resonator, the need to separate the input and output coupling lines from the resonator cavity by the use of vacuumtight microwave windows is avoided by instead having the tubular line(s) for coupling electromagnetic energy into and out of the cavity open into the resonator cavity from below the cavity.

5 Claims, 3 Drawing Figures



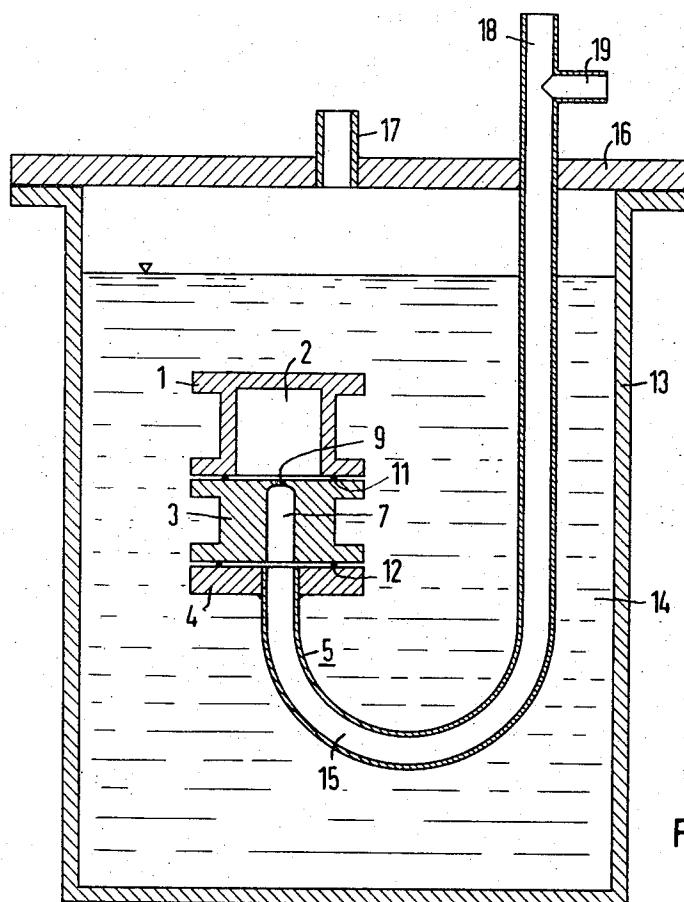


Fig. 1

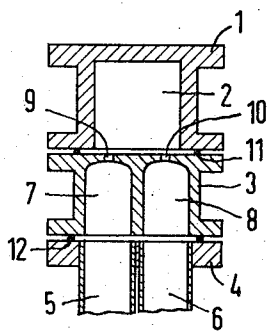


Fig. 2

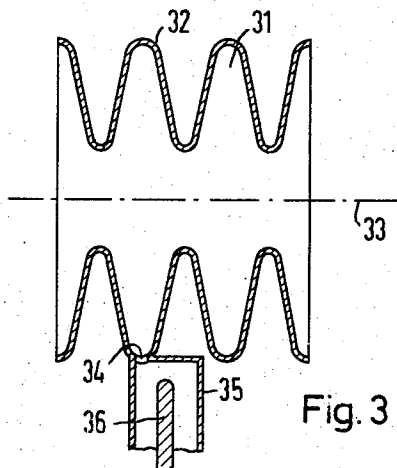


Fig. 3

SUPERCONDUCTING CAVITY RESONATOR

BACKGROUND OF THE INVENTION

The invention concerns a superconducting cavity resonator with at least one tubular line, for coupling electromagnetic energy in and out of the cavity, which opens into the resonator cavity without vacuumtight separation.

Superconducting cavity resonators, which either consist completely of superconductive material or have a superconducting surface bounding the resonator cavity, are particularly well suited as resonators and as separators for particle accelerators. Such resonators also have other applications, for instance, as frequency standards. Niobium is usually preferred as the superconductive material for cavity resonators, but other superconductive materials, particularly lead, can also be used.

As a rule, one or several tubular lines, for instance, rectangular waveguides or tubular coaxial lines which open into the resonator cavity are utilized for coupling electromagnetic microwave energy into and out of the resonator cavity.

As the alternating currents produced by the microwave fields in the walls of the cavity resonator only have a very small depth of penetration into the superconductive material, the condition of the surface layer in which these ac currents flow is of great importance. Particularly the surface resistance and therefore the quality factor Q of the resonator, as well as the critical magnetic field H_c^{ac} measured under the action of alternating fields, depend substantially on the condition of the surface. A high critical magnetic field is important so that the cavity resonator can be operated with high-frequency power as high as possible with at the same time, high Q . If the critical magnetic field is exceeded, the ac losses increase steeply and the quality Q of the resonator decreases considerably.

In order to achieve a high Q and a high critical magnetic field H_c^{ac} , on the one hand the cavity resonators should be initially manufactured with surfaces already as smooth and free of contamination as possible and on the other hand, provision should be made during the operation of the cavity resonators so that the surface properties do not deteriorate. For smoothing and purifying the surfaces during manufacture, chemical and electrochemical polishing methods are used, and in the case of niobium surfaces, annealing methods are also used. When annealing is used, in addition to a purification of the niobium surface by outgassing, a grain growth of the niobium also occurs so that the number of grain boundaries at the niobium surface is decreased. In niobium cavity resonators, particularly high Q and critical magnetic fields can be achieved by providing the surface bounding the resonator cavity with a niobium oxide layer through anodic oxidation. Through the oxidation of the surface, the resonator surface effective for superconduction is relocated away from the surface proper into a lower and purer niobium layer. At the same time, the niobium oxide layer serves as a protective layer for this deeper-located effective surface as described in "Physics Letters," vol. 34A, 1971, p.439 to 440.

During operation the superconducting cavity resonator must be cooled to low temperatures. For this purpose, the resonator is arranged in the helium tank of a

cryostat. By pumping off the helium vapor above the liquid helium present in the helium tank, temperatures down to 1.2 K can be obtained. Generally, prior to the present invention, the tubular lines for coupling the electromagnetic energy in and out of the resonator cavity were introduced from above into the cooling-medium vessel of the cryostat and also open into the resonator cavity from above. Also at first in known resonators, these lines opened directly into the resonator cavity and were not separated from the resonator cavity in a vacuumtight manner, i.e., the entire interior of the lines formed a common gas space with the resonator cavity, so that the lines could be utilized at the same time for evacuating the resonator cavity as described in "Journal of Applied Physics," vol. 39 (1969), p.2606 to 2609 and 4417 to 4427.

However, more accurate investigations on resonators with bare, superconductive surfaces and lines opening into the resonator cavity from above demonstrated that the quality of the cavity resonators decreased over an extended period of operation. This effect was explained by surface contamination, which gets from the parts of the vacuum system which are at room temperature, i.e., particularly from the tubular feed lines, to the resonator cavity which is at a low temperature, due to cryopumping action. To avoid this surface contamination, the parts of the tubular feed lines which are at a higher temperature, were separated from the resonator cavity in a vacuumtight manner by means of inserted vacuumtight microwave windows made of for instance, ceramic material. In such resonators for evacuating the resonator cavity, there is provided between the microwave window and the resonator cavity proper a separate pump line which is hermetically sealed off after the cavity resonator is evacuated, before the latter is placed in the cryostat. If the microwave window which closes the resonator cavity off against the tubular feed line is immersed in the liquid helium together with the resonator cavity, the entire vacuum-wise boundary of the resonator cavity is at the same temperature, and gases can no longer get from warmer parts of the vacuum system to the walls of the resonator cavity by cryopumping action. Such systems are described in "Applied Physics Letters," vol. 13 (1968), p.390 to 391; "Applied Physics Letters," vol. 16, (1970), p.333 to 335; article by M. A. Allen et al., "Superconducting Niobium Cavity Measurements at SLAC," SLAC-PUB-890, Stanford Linear Accelerator Center, Stanford, Cal., March 1971.

Separating the input and output coupling lines from the resonator cavity by means of vacuumtight microwave windows, however, is a very expensive design. In practice it is often difficult to even manufacture suitable microwave windows. Closing off the resonator cavity vacuumtight against the tubular input and output lines by a microwave window has the further disadvantage that gases that may enter into the resonator cavity due to leaks cannot be pumped off while the resonator is in operation. This could be accomplished only by additional pump lines, which again bring with them the danger of contamination because of the cryo-pump action.

In a superconducting cavity resonator with at least one tubular line which opens into the resonator cavity for coupling electromagnetic energy into and out of the resonator, it is an object of the present invention to avoid the vacuumtight separation of the line from the

resonator cavity by a microwave window, without impairment of the functioning and, in particular, of the Q of the resonator.

DESCRIPTION OF THE INVENTION

According to the invention, this problem is solved by letting the line open into the resonator cavity from below.

The solution according to the present invention is based on the surprising discovery that, contrary to previous understanding and belief, contamination due to cryo-pumping action has only a relatively small influence on the Q of the superconducting cavity resonators. A much stronger detrimental effect is that of small dirt and dust particles, which in spite of the most careful cleaning procedures remain in the tubular feed lines to the resonator cavity and, in the case of feed lines opening into the resonator cavity from above, drop into the resonator cavity and carbonize in the strong microwave field prevailing there. Such dirt particles can drop into the resonator cavity even if it is closed off vacuum-tight by a microwave window, since they can drop off from this microwave window itself or from the parts located between the microwave window and the resonator cavity proper. This is because these parts cannot be annealed to completely remove dust and dirt, because of the usually required solder and sealing joints and the different materials used, and also because these parts cannot be subjected to the other chemical and electrochemical methods for cleaning the resonator surface. It should also be noted that in a high vacuum, even the smallest dirt or dust particles drop down in free fall due to the absence of any air resistance.

In accordance with the present invention, by arranging the tubular line, to open into the resonator cavity from below, any dropping of dust or dirt particles into the resonator cavity is avoided without the need for a vacuum-wise separation of the resonator cavity from the parts of the tubular line which are at a higher temperature. The line can therefore serve at the same time as a pump line for evacuating the resonator cavity.

An opening of the line or lines from below is understood here to mean that the line rises before opening into the resonator cavity. In other words, the last section of the line before opening into the resonator cavity should run at an angle against the horizontal or vertically from below, so that the parts of the line adjacent to the opening of the line are at a lower level than the opening itself. The line coming from below can also open into a laterally situated part of the wall of the resonator. However, it is preferable to let the line open into the resonator cavity at the bottom side of the resonator.

In the case of several tubular lines opening into the resonator cavity for coupling electromagnetic energy in and out, it is preferable that all lines open into the resonator cavity from below, so that in no case can dirt or dust particles drop into the resonator cavity from above. Also specially provided tubular lines which do not serve for coupling electromagnetic energy in and out but serve exclusively as pump lines for evacuating the resonator cavity, should preferably open into the resonator cavity from below. Such additional pump lines may be of advantage particularly in resonators with large physical dimensions.

The lines brought through the bottom of the cryostat in which the cavity resonator is situated, may open into

the resonator cavity coming from below in a straight line. However, it is particularly advantageous if before opening into the resonator cavity, the line or lines form a bend. Since gas molecules that may come from the end of the line which is at a higher temperature cannot traverse in a straight line, such a bend forms a cooling trap for gases entering through the line and thereby additionally prevents the contamination of the resonator surface due to the already mentioned cryo-pumping effect. It is particularly advantageous if in an arrangement of the cavity resonator in the coolant vessel of a cryostat the bend of the line or lines, which serves as a cooling trap, is situated lower in the coolant vessel than the lowest point of the resonator cavity. In such an arrangement, when the coolant is filled into the coolant vessel of the cryostat, the bend in the line is cooled down first so that residual gases that may be present in the resonator cavity are drawn off from the resonator cavity into the bend through the cryo-pumping effect of the bend. In addition, if the line or lines has a bend the line can be introduced into the cryostat from above the cryostat and still achieve the advantages of the present invention since the portion of the line entering the resonator cavity will still be entering from below the cavity.

The opening of the lines into the resonator cavity from below has advantages not only in the case of cavity resonators with bare, superconductive surfaces, but also in the case of a niobium cavity resonator, the surface of which is anodically oxidized since even in the case of a surface protected in this manner, dirt and dust particles dropping into the resonator cavity have a detrimental effect on the electric properties of the resonator.

DESCRIPTION OF DRAWINGS

The invention will be explained further with the aid of several figures and examples.

FIG. 1 shows schematically, in cross section, a cavity resonator of the TE₀₁₁ type arranged in the coolant vessel of a cryostat with coupling lines entering from below;

FIG. 2 shows a different cross section through the cavity resonator according to FIG. 1;

FIG. 3 shows schematically, in a longitudinal cross section, part of a separator structure of the HEM₀₁₁ type with a coupling line entering from below.

The cavity resonator of the TE₀₁₁ type shown in FIGS. 1 and 2 is operated at X-band, i.e., in the range of about 8 to 12 GHz. The longitudinal cross section shown in FIG. 2 is perpendicular to the longitudinal cross section shown in FIG. 1. The cavity resonator consists of a cupshaped resonator part 1 with a resonator cavity 2 in the form of a circular cylinder and is closed downward by a coupling member 3. At the bottom of the coupling member 3 is attached a disc-shaped flange 4, into which two rectangular waveguides 5 and 6 which serve as the coupling lines are soldered or welded. Inside the coupling member 3 are provided two coupling stubs 7 and 8, which continue the lines 5 and 6 toward the resonator cavity 2. The coupling stubs 7 and 8, which form part of the coupling lines, open into the resonator cavity 2 from below through coupling apertures 9 and 10. For sealing against the outside, indium ring seals 11 and 12 are provided between the resonator part 1, the coupling member 3 and the flange 4. In the assembly of the cavity resonator the individual

resonator parts are bolted together. The overall resonator is located in the helium vessel 13 of a conventional cryostat, which can be filled with liquid helium 14. The parts of the cryostat which serve for thermal insulation and surround the helium vessel, such as vacuum spaces and a radiation shield, are not shown in FIG. 1. The tubular lines 5 and 6 form a bend 15 within the helium vessel 13 and are brought out of the cryostat upward through the cover 16 of the cryostat. A pump connection 17 for pumping off the helium vapor is provided in the cryostat cover. For feeding in the microwave energy, the lines 5 and 6 may be connected at their end 18, which is at room temperature, with a suitable microwave source, for instance, a klystron. To evacuate the lines 5 and 6, and the resonator cavity 2, there is provided at at least one of the lines 5 or 6 a branch 19 which is suitably arranged, i.e., so that it does not interfere with the propagation of the microwaves, which can be connected with a vacuum pump. The bend 15 is situated in the coolant tank at a lower level than the lowest point of the resonator cavity and serves as a cooling trap for gas molecules that may enter from the ends 18 and 19 of the lines 5 and 6. The lines 5 and 6 and the resonator cavity 2 are already evacuated via the connection 19 prior to immersion of the resonator into the helium bath 14. If the resonator is immersed into the helium bath, or after insertion of the resonator into the helium vessel 13, the latter is filled with helium, the bend 15 is the first part of the whole arrangement cooled to a low temperature.

DESCRIPTION OF EMBODIMENTS OF THE INVENTION

In a specific example of an embodiment of the cavity resonator shown in FIGS. 1 and 2 the parts 1, 3 and 4 consist of solid niobium. The resonator cavity 2 has an inside height and an inside diameter of 41 mm; the coupling apertures 9 and 10 have a diameter of 1.5 mm each. The coupling stubs 7 and 8 each are 40 mm long and have a rectangular cross section of about 10×23 mm². The rectangular waveguides 5 and 6, which may, for instance, consist of alloy steel, have the same inside cross section. The niobium surfaces bounding the resonator cavity 2 are smoothed first mechanically and subsequently further by chemical or electrochemical polishing methods and are finally provided with a protective niobium oxide layer of between about 0.1 and 1 μ m thickness by anodic oxidation. All other parts of the resonator as well as the waveguides 5 and 6 were very carefully cleaned.

A resonator treated in this manner was first inserted into the helium vessel 13 of the cryostat with feed lines 5 and 6 opening into the resonator from above, i.e., upside down from the illustration in FIG. 1, the feed lines 5 and 6 being brought out in a straight line without a bend through the cryostat cover 16. With this arrangement of the resonator an unloaded Q_0 of about $2 \cdot 10^9$ with a critical magnetic field of about 50 milliteslas was measured at a temperature of about 1.5 K and a microwave frequency of 9.5 GHz. After disassembling the resonator, carbonized dirt particles were found at the underside of the resonator cavity underneath the coupling holes.

When the feed lines 5 and 6 were brought in from below in the manner shown in FIG. 1, an unloaded Q_0 of $2 \cdot 10^{10}$ and a critical magnetic field of about 110 milliteslas were achieved with the same resonator, the

same surface treatment and also otherwise unchanged conditions. After disassembling the resonator, no changes of any kind could be ascertained at the walls of the resonator cavity. Comparable values of the Q and the critical magnetic field have heretofore been reached only with resonators, where the resonator cavity was separated in a vacuumtight manner from the feed lines by microwave windows. In contrast, with the present invention the costly microwave window with all the disadvantages connected therewith is eliminated without impairment of the good electrical properties of the resonator. Similar improvements have also been achieved by bringing in the lines from below in niobium resonators with bare inside surface.

Regarding the bending of the rectangular waveguides, it should be noted that in order to obtain the lowest possible reflections in the curved part of the waveguide, it is advisable not to force maintenance of the original rectangular cross section shape through lateral guide rolls in bending. It is electrically better to fill the wave guide prior to bending with an incompressible material and to bend it around a core of suitable diameter without lateral guidance. The cross section of the waveguide is deformed trapezoidally in the process. Lead is well suited as such filler material. If one wishes to give the waveguide an intermediate anneal for stepwise bending, the use of a copper core has been found practical, which can subsequently be dissolved by means of nitric acid in the case of a waveguide consisting of alloy steel.

Feeding in the tubular lines from below is applicable independently of the specific shape of the cavity resonator for the most varied types of resonators. For instance, FIG. 3 shows a section of a particle separator for particle accelerators of the HEM₀₁₁ type in a lengthwise cross section. The resonator wall 32 which encloses the resonator cavity 31 and consists, for instance, of niobium is of rotational symmetry with respect to the longitudinal axis 33, so that the cross section of the resonator cavity is always circular. A tubular line 35 for coupling in the microwave energy opens into the resonator cavity 31 from below via a coupling hole 34. The line 35 may, for instance, be a rectangular waveguide, but it can also be designed as a coaxial line and have an additional inner conductor 36. In operation the resonator according to FIG. 3 is arranged in a cryostat with horizontal longitudinal axis. The line 35 can then be bent similarly as the line 5 shown in FIG. 1 and be brought out of the cryostat at the top. Another possibility consists, as already mentioned, of feeding the line from below through the bottom of the cryostat.

The examples of embodiments shown in the figures can be modified in many ways. The line 5 in FIG. 1 can, for instance, have also several bends. However, it is always essential that the line opens into the resonator cavity from below.

What is claimed is:

1. A superconducting cavity resonator with one or more tubular lines for coupling electromagnetic energy in and out of the resonator with a coolant vessel surrounding said superconducting cavity resonator wherein the invention comprises tubular lines for coupling having a bend prior to opening into said resonator cavity, with said lines opening into said cavity from below and said bend situated in the coolant vessel lower than the lowest point of the resonator cavity and

7

acting as a cooling trap for gas molecules entering through said lines.

2. The superconducting cavity resonator of claim 1 wherein said lines open at the bottom of said resonator into said resonator cavity.

3. The superconducting cavity resonator of claim 1 wherein said lines open into said resonator cavity without vacuumtight separation.

4. The superconducting cavity resonator of claim 1 and further including one or more pumping lines open-

8

ing into the resonator from below, said pumping lines having a bend before opening into said cavity, which bend is disposed lower in the coolant vessel than the lowest point of the resonator cavity, to thereby serve as a cooling trap for the gaseous molecules entering through the pumping line.

5. The superconducting cavity resonator of claim 4 wherein said pumping lines open at the bottom of said resonator into said resonator cavity.

* * * * *

15

20

25

30

35

40

45

50

55

60

65