IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-15, NO. 1, JANUARY 1979

DEVELOPMENT AND PRODUCTION OF SUPERCONDUCTING RESONATORS FOR THE ARGONNE HEAVY ION LINAC*

K. W. Shepard, C. H. Scheibelhut, P. Markovich,
R. Benaroya and L. M. Bollinger+

ABSTRACT

The first six niobium split-ring resonators for the Argonne Heavy-Ion Energy Booster have been completed. The average performance at 4.2K is an accelerating gradient of 3.7 MV/m or an effective accelerating potential of 1.3 MV per resonator for an rf input of 4 W/resonator. The resonators are constructed in part of an explosively bonded Nb-Cu composite material which performs well for rf surface fields of at least 200 G. In initial tests, the resonators frequently exhibit thermal instability at $E_a < 3$ MV/m because of several types of microscopic surface defects. The methods used for locating, identifying, and removing these defects are discussed.

I. INTRODUCTION

This paper reports the recent development and initial production experience with superconducting niobium split ring resonators for the Argonne Heavy-Ion Energy Booster.[1]

Shown in Fig. 1, the 97 MHz resonator is as previously described, and consists of an all niobium drift-tube and inductive loop assembly inside a cylindrical housing formed of niobium explosively bonded to a copper backing.[2,3] At this writing, seven such resonators have been completed; a prototype unit currently used for beam bunching, and the first six of twelve resonators presently under construction for the linac proper.

In early tests of the prototype, the maximum rf field was limited by thermal instability caused by small surface defects.[3] This problem has also been frequently encountered in subsequently produced resonators. In the following section, methods of locating such defects, the types of defects encountered, and means of removal are described.

The prototype tests also showed excessive rf loss in the explosively bonded niobium-copper composite.[3] In the third section, further development of the composite material is described.

Finally, the performance to date of the resonators being produced for the linac is discussed.

II. THERMAL INSTABILITY AND SMALL SURFACE DEFECTS

The Argonne split-ring resonators are of high complexity for superconducting rf structures. Each resonator consists of 25 separate niobium parts joined by 32 electron beam welds. The least defect in the niobium surface, such as microscopic fissures, impurity inclusions, etc., can degrade resonator performance to an unacceptable extent. Most of the resonators so far constructed have exhibited defects during initial tests. Adequate performance has been obtained only by a process of identifying and removing the defects. Therefore it has been essential, not only for resonator development, but also for resonator production, to have a means of rapidly and accurately locating sources of rf loss within a resonator.

Manuscript received September 28, 1978.

*Work performed under the auspices of the U.S. Department of Energy.

+Argonne National Laboratory, Argonne, Illinois 60439

Second Sound Measurements

The most serious defects so far encountered can be generally classified as a localized source of rf loss in a region of high surface magnetic field ($B > 100$ G). The localized rf power loss causes heating of the defect and adjacent superconducting surface. In a sufficiently large rf field, the region adjacent to the defect is heated to the superconducting transition temperature. At this point the resonator becomes thermally unstable, and a normal region grows rapidly until the rf energy initially present in the resonator is converted to heat, i.e., the instability is manifested at a well-defined critical field level by a sudden collapse of the rf field in the resonator. The time required for the collapse is typically two or three milliseconds.

The rf power required to initiate an instability is generally quite small. In the present resonators a localized defect dissipating only a few milliwatts could cause a thermal instability at an accelerating field $E_a < 3$ MV/m. A normal region 0.1 mm in diameter would constitute such a defect. It is not practical to find such defects directly by visual inspection: they can, however, be located with fair precision by exploiting the superfluid properties of liquid helium.

Thermal instabilities occur in regions of high surface magnetic field, which in the Argonne split-ring resonator is the inductive loop, a .090 inch wall niobium tube the interior of which is cooled by liquid helium. When a resonator goes unstable, typically a joule of heat energy is injected into the liquid helium in a few milliseconds. If the resonator is operated at $T < 2.17$K, the helium is superfluid and a second-sound wave propagates away from the region of heat injection at a velocity of $\sim$20 m/sec.

By locating several germanium resistance thermometers inside the tube, the second sound pulse can be observed as a temperature fluctuation. The time of arrival of the pulse at a given thermometer is determined by the time of flight from the heated region, which is centered on the defect causing the thermal

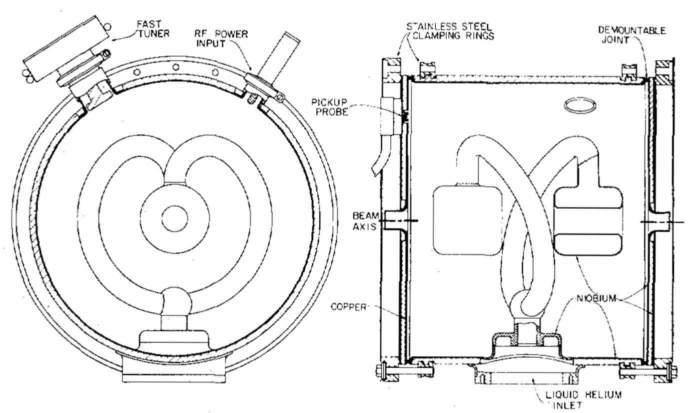

Fig. 1. The split-ring resonator. The overall length is 17 inches. The drift tube and inductive loop assembly is made of niobium, the outer housing of niobium explosively bonded to copper.

breakdown. By measuring the time of flight to several differently placed thermometers, the location of the defect can be unambiguously determined. This procedure is particularly simple for the split-ring resonator, since the loading tube provides an essentially one-dimensional system.

Figure 2 shows an oscilloscope photograph of the phenomenon observed. The upper trace shows the rf field level in a split-ring resonator, which is driven by an rf pulse to a field $E_a = 3.0$ MV/m. At this field level the resonator becomes thermally unstable and the rf field collapses. The lower trace displays the temperature of a thermometer located inside the inductive loop. The thermometer is a Cryocal germanium resistance thermometer with the top of the casing filed off to expose the germanium element directly to the superfluid. Thus, the thermometer is in an open ended tube 6 mm long, which responds to a second sound pulse as a quarter-wave resonator, "ringing" in temperature at a frequency of $\sim$1 kHz. In Fig. 2, this begins 13 msec after the collapse of the rf field, indicating that the defect in the superconducting resonator is 26 cm from the thermometer. It should be noted that Fig. 2 is a superposition of 10 events, showing the high degree of repeatability of the process.

In practice, this diagnostic technique is straightforward and typically locates a defect to within 1 or 2 cm, which then permits microscopic examination of the region in question and some form of local repair.

Types of Defect Observed

Three types of defect have been encountered: small beads of niobium attached to the surface and apparently caused by spatter from beam welding, small fissures in or near welds, and impurity inclusions.

Figure 3A shows the initial performance of the second linac resonator. The sharp decrease in Q at low field levels exhibits hysteresis, and the resonator is thermally unstable at a field level $E_a = 1.2$ MV/m. The second sound data showed a defect midway along one arm of the inductive loop. Visual examination revealed a .015 inch diameter bead of niobium within the region indicated by the second sound data. The behavior shown in Fig. 3A seems explainable in the following way. The hysteresis at low field levels is caused by the switching of the bead itself between the superconducting and normal states and indicates poor thermal contact between the bead and the resonator. The decrease in Q with increasing field level is caused by heating of the bead which increases the normal state surface resistance. At $E_a = 1.2$ MV/m the heat load into the surrounding niobium is sufficient to drive it normal and the resonator becomes unstable. Removal of the bead resulted in the performance shown in Fig. 3B.

In the fifth resonator, similar behavior was observed, with a much smaller ($\sim$10%) hysteretic change in Q, and with a higher point of thermal instability ($E_a = 2.8$ MV/m). In this case, a .005 inch diameter niobium bead was found to cause the instability. The bead was hardly visible under microscopic examination because of lack of contrast with the background, and could probably not have been located without the aid of the second sound data.

The other defects encountered have not caused observable rf loss prior to thermal breakdown.

In two cases, for which thermal instability occurred in the range $2.5 < E_a < 3$ MV/m, second sound data indicated defects at electron beam welds. Microscopic examination revealed small fissures a few mm long in each of these welds. At least one of these fissures did not appear until the final electropolish of the resonator prior to testing.

The most troublesome defects encountered occurred in the prototype resonator. In early tests, this resonator was thermally unstable at a field level $E_a \simeq 2$MV/m. Second sound data indicated one or more defects on the inductive loop, but visual observation showed no obvious flaw. Repeated electropolishing shifted the region of breakdown several cm, but did not greatly improve performance.

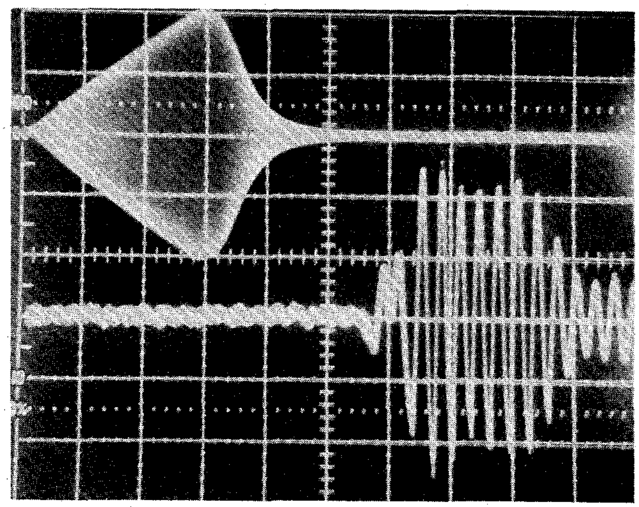

Fig. 2. Thermal breakdown at 1.9K and associated second-sound pulse. The horizontal scale is 10 msec/division. The upper trace shows the rf field in the resonator, the lower trace the temperature of a sensor in the liquid helium inside the inductive loop.

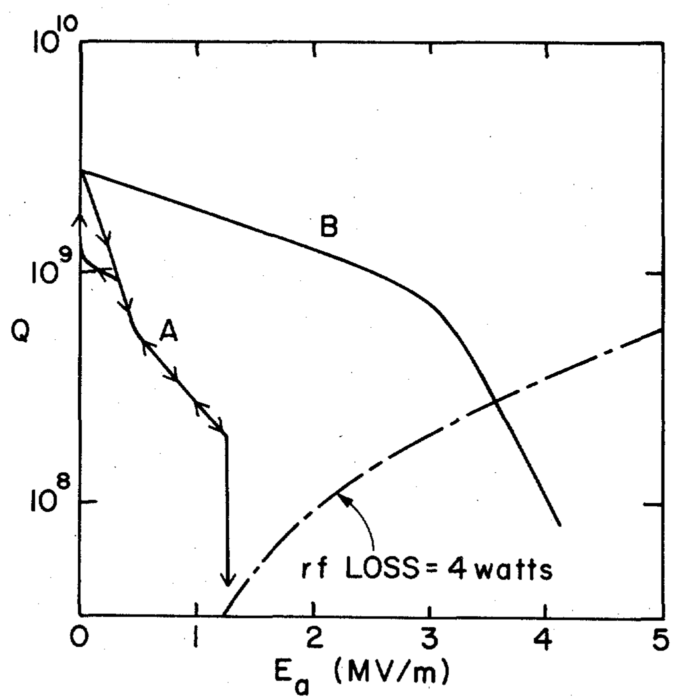

Fig. 3. Performance of the second linac resonator at 4.2K. Curve A is the result of the initial test. Curve B, the second test, performed after removing a small defect on the inductive loop.

Thick anodic films are used industrially as a test for small regions of impurity of severe cold work in niobium and other refractory metals.[4] Following this procedure, the resonator was anodized to form an oxide 1200Å thick. Visual inspection then revealed a number of slightly discolored regions, typically 1 mm in diameter, scattered over the region in which breakdown had occurred. In thinner anodic films, no discoloration was observed. The discolored spots were eliminated by filing away the affected regions. Removal of as much as 1 mm of material from the original surface was required. The resonator was then electropolished and subsequently found to operate stably at field levels of at least E_a = 3.6 MV/m.

Removal of Defects

In all cases thus far, after positive identification of a defect, removal has been straightforward.

The beads of niobium were removed with abrasive, and the abraded region then electropolished to eliminate any work damage. Of the two fissures encountered, one required re-welding, but the other was eliminated by electropolishing 75μ from the weld area. As has been described, impurity inclusions were also eliminated by removal of niobium.

A convenient technique for removing niobium from a resonator is electropolishing. However, heavy electropolishing of an entire resonator is impractical since it would change the rf eigenfrequency, increase surface roughness, and possibly uncover or create new defects. Thus a method of electropolishing small areas of a resonator was developed. It was found that a film of PVC, applied by brushing on a solution of PVC in acetone,* adhered well to the niobium surface and resisted the action of the HF-H_2SO_4 mixture required for electropolishing. The film provides an effective mask to prevent electropolishing of the covered region and can be removed by dissolving with acetone.

III. NIOBIUM-COPPER COMPOSITE MATERIAL

The cylindrical housing and end flanges of the resonators are formed of a niobium-copper composite, allowing the niobium to be cooled by thermal conduction through the copper, thus eliminating the need for circulating liquid helium around the housing. This approach was chosen to reduce construction costs, simplify the cryogenic system, and to increase the mechanical ridigity of the resonator.[3]

The composite is formed of 1/16" niobium sheet, explosively bonded to cold-rolled ETP copper plate. The bond provides good thermal contact to the niobium and withstands repeated cycling to liquid helium temperatures. Forming procedures, such as rolling and die-forming are straightforward: reductions in area of approximately 50% can be obtained.

In joining, electron beam welding is used. The copper backing is removed by machining 1/8" back from the weld line. Care must be taken to insure complete removal of copper to prevent cracks and fissures in the weld. A brief chemical etch of the bared niobium with 8N nitric acid to remove traces of copper was found necessary to produce good welds.

In initial tests of the prototype resonator, rf losses in the composite material were excessive, indicating a surface resistance $R_s \cong 2 \times 10^{-6}\,\Omega$ at 4.2K. Comparison of the residual resistivity of niobium from the composite with the parent material indicated no appreciable increase in interstitial impurities from the explosive bonding process. Chemical analysis failed to reveal any significant increase in contaminants. However, electropolishing the resonator to remove a 150μ layer of niobium reduced the surface resistance of the composite material by a factor of three.

In forming the composite material discussed above, the niobium was directly exposed to the hot gas produced by an ammonium nitrate explosive. Although the precise mechanism could not be ascertained, it seemed probable that this process was causing the high surface resistance. Thus the bonding process was modified by gluing a 1/32" sheet of rubber to the exposed niobium surface to prevent direct exposure to the explosive.+

The six linac resonators tested were made with the modified niobium-copper composite, and the observed performance establishes an upper bound for the surface resistance of the composite of $R_s < 3 \times 10^{-7}\,\Omega$ at 4.2K for peak surface fields $B_s \leq 160$ G. The bound results from attributing all rf losses to the composite material and is probably conservative. No performance limitation due to rf losses in the composite has been observed at surface fields up to 200 G.

IV. PERFORMANCE OF THE LINAC RESONATORS

Although diagnostic testing of each resonator is necessary, the level of effort required is not excessive. Of the six resonators so far completed, two performed well in the initial test. With the remaining four, one diagnostic test was sufficient to eliminate surface defects, and the resonators performed well in the second test.

Figure 4 shows the performance at 4.2K of the six linac resonators so far completed. The average accelerating field obtained is E_a = 3.7 MV/m at the design rf loss of 4 W/resonator which provides an effective accelerating potential of 1.3 MV/resonator.

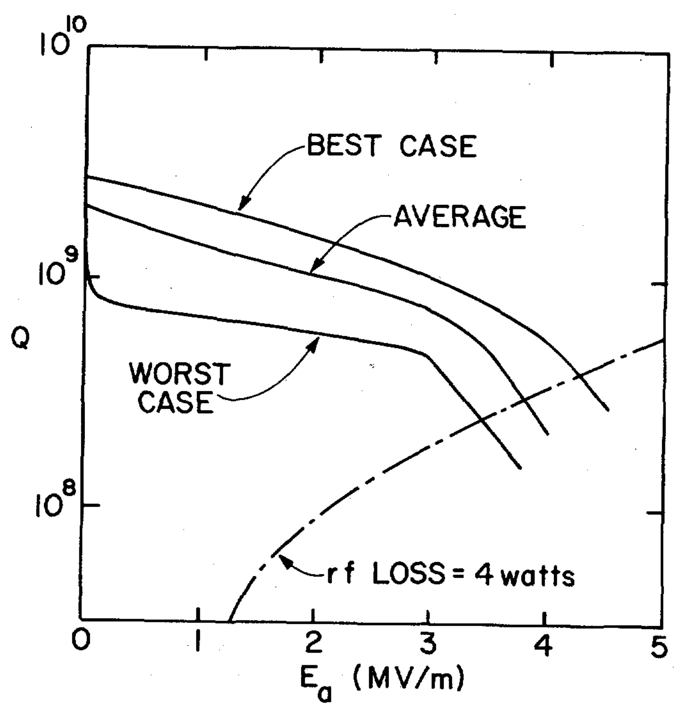

Fig. 4. Performance of the first six linac resonators at 4.2K. The accelerating field E_a is defined as the energy gain per unit charge for a synchronous particle divided by the interior length of the resonator (14 inches).

*Packaid No. 4, Seal-Peel Inc., Troy, Michigan.

+Suggested by A. Hare of Northwest Technical Industries, Port Angeles, Washington.

The fall-off in Q at high field levels is accompanied by x-ray emission indicating electron loading. The performance shown in Fig. 4 was obtained after conditioning the resonators for one hour by operating at as high a field level as possible, typically 10 to 30 W rf input, in He gas at a pressure of 2×10^{-5} torr.[5]

Cycling to room temperature and storage in dry nitrogen at 1 atm for periods of at least several weeks have not been found to produce any significant change in performance.

V. CONCLUSIONS

Present construction and diagnostic techniques produce superconducting resonators of adequate performance for the Argonne Heavy-Ion Energy Booster. A remaining question is the long-term stability of resonator performance under operating conditions.

ACKNOWLEDGEMENTS

The authors would like to thank R. Breuss, E. Gutowski, and W. Legatzke of the Argonne Central Shops Staff for their efforts in constructing the resonators.

REFERENCES

1. L. M. Bollinger, R. Benaroya, B. E. Clifft, A. H. Jaffey, K. W. Johnson, T. K. Khoe, C. H. Scheibelhut, K. W. Shepard, and T. P. Wangler, Proceedings of the 1976 Proton Linear Accelerator Conference, 95, September 1976, AECL - 5677.

2. R. Benaroya, L. M. Bollinger, A. H. Jaffey, T. K. Khoe, M. C. Olesen, C. H. Scheibelhut, K. W. Shepard, and W. A. Wesolowski, IEEE Trans. Mag. MAG - 13, 516 (1977).

3. K. W. Shepard, C. H. Scheibelhut, R. Benaroya, and L. M. Bollinger, IEEE Trans. Nucl. Sci. NS - 24, 1147 (1977).

4. W. McDonald, Teledyne Wah Chang Corp., private communication.

5. H. A. Schwettman, J. P. Turneaure, and R. F. Waites, J. Appl. Phys. 45, 914 (1974).