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Information derived from a visit to Siemens AG, Erlangen, FRG, to discuss their work on superconducting microwave cavities is presented. The results obtained with niobium and niobium tin (Nb_3Sn) over the last few years are reviewed. Siemens' current interests are to continue work with Nb_3Sn, to explore new TM-cavity designs, improve cavity reproducibility and to produce less expensive cavities.

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SUPERCONDUCTING MICROWAVE CAVITY RESEARCH AT SIEMENS

I. Introduction

The Siemens AG, Research Laboratories at Erlangen, Federal Republic of Germany (FRG), were visited in December 1977 to review recent progress in the study of materials and techniques for superconducting microwave cavities with high quality factors and high critical flux densities. In particular, it was desired to learn where further significant progress may be expected, and what problems seem to block progress toward practical microwave cavities with useful critical flux densities. As Siemens has been well known for many years for its work in the field, it was a logical place to learn "where the action is" in this field in Europe today. Dr. Rolf Gremmelmaier, the director of the superconductor materials work, and his staff, including Drs. H. Pfister, B. Hillenbrand, H. Diepers, and Penczynski were interviewed. The group proved to be extraordinarily hospitable, and they freely shared their research results and expectations as to where progress might, or might not, be made in the future.

II. Background

The prospective microwave applications of superconductivity have been widely discussed over the last decade. No attempt is made here to review that rather extensive literature. As an arbitrary starting point, however, it is noted that Professor W.A. Little at Stanford very recently wrote an excellent assessment of potential Navy applications of superconductivity, including reference to microwave cavities.[1] He has also reported on some of the limits imposed on cavity performances by the laws of physics—as we now understand them.[2] Little pointed out that microwave-cavity Qs as high as 10^{11} have been reported[3], and that peak magnetic fields of 10^3 Oe have been achieved by the Siemens group. He also reviewed some of the prospects for critical field enhancement by nonequilibrium and field dependent effects.

As early as 1971, Siemens published results on niobium cavities at x-band. This as well as much subsequent work, was performed for the Nuclear Research center at Karlsruhe, FRG. The best results achieved then were with cavities machined from solid niobium. They learned that an anodic oxide film allowed an increase in Q as well as the critical magnetic field. At that time a best Q_0 of 1.1×10^{10} was obtained at 1.4 K and H_{max} of 52 mT for degassed, chemically polished surfaces, with an oxide film. These and related surface processing techniques are still considered critical to Siemens' success, as the following review will show. However, now the niobium tin alloy (Nb_3Sn) is considered to have the greatest potential for practical application. Siemens' hope that, by using Nb_3Sn cavities, they will eventually be able to work at 4.2 K rather than the 1.4 K that has been used for the best niobium results—with much simplification of the cryogenics required, while achieving the same level of magnetic field.

III. The visit to Erlangen

At the outset Pfister reviewed, in general, the activities of Siemens in the microwave cavity field. They have supported the Karlsruhe group by contributing cavity materials' preparation and design expertise. Karlsruhe currently has a group of 50 people involved principally in particle acceleration-separator design for CERN. A new interest at Siemens is to examine the possibility of using superconducting L-band storage cavities for DESY (Hamburg synchrotron storage ring). Another customer described was the University (Gesamt Hochschule) of Wupperthal where a group under Professor Piel is planning to build a smaller linear electron accelerator. This small group has been working on this problem for two or three years. They are principally concerned with x-band cavities.

In already completed programs, Siemens has fabricated cavities (L-band) for the Karlsruhe group and x-band niobium cavities for both Wupperthal and Karlsruhe. Both groups have some interest in Nb_3Sn. I gained the impression that there is now some new support for the field and that applied research and advanced engineering design of specialized cavities is continuing.

I spent a considerable period of time with Hillenbrand, who gave me a rather thorough review of Siemens' work in the field as well as his assessment of the current state-of-the-art. He bore heavily on the importance of cavity surface preparation, as the key to Siemens' success. Earlier work on niobium was described, then the Nb_3Sn effort. As mentioned earlier, the most successful niobium cavities are milled out of solid niobium. These cavities (for 9.5 GHz) are 50 mm in diameter and 50 mm deep. After the machining process the cavities are electropolished in a solution of 90% concentrated H_2SO_4 plus 10% HF, during which about 100 microns of material is removed. Hillenbrand emphasized that an oscillating current is required to achieve good electropolishing. Next, the surfaces are "oxypolished" by anodization techniques. This is followed by rinsing in H_2O_2 and H_2O, stripping in HF, followed by an ultrasonic cleaning treatment. Siemens has not found it always necessary to employ a degassing treatment, as done by others, on the final cavity.

Another example of the thoroughness of the Siemens' methodology is an inverted, wet-cavity installation, developed to assure that no dust particles could reach the cavity via the waveguide connection. The cavity is installed upside down, waveguide entering from the bottom. The waveguide is bent into the form of a sink trap, such that any dust particles should collect at the bottom of the trap. In the cavity itself, acetone is injected through a small port, and acetone vapor is flushed out of a second port carrying with it any residual dust particles! Hillenbrand admitted that this process might now be overemphasized. The actual influence of dust particles (as microroughness of walls) has not yet been measured.

Two types of cavities have been studied, TE and TM. The TM_{10} is of direct interest in the particle accelerator business. However, to date, the TE mode cavity has been studied in more detail. Interestingly enough, for niobium Siemens has achieved a higher B_c^{ac} (maximum flux density at the cavity wall) with TE rather than TM (159 mT versus 149 mT). These figures are in the literature and have not to my knowledge been surpassed to date. The corresponding values of Q were given as $Q_{TE} = 1 \times 10^{10}$ and $Q_{TM} = 3 \times 10^9$. Siemens personnel did not readily volunteer an answer to the key question of whether these values can be pushed further. Rather than struggle for higher values of B_c and Q, the Siemens people seem more interested in high-field temperature dependences and ways of improving cavity stability. Hillenbrand stated that for $B_c^{ac} > 120$ mT we are limited by thermal conductivity for T ∿ 1.8 K and at a lower temperature T ∿ 1.3 K the appearance of magnetic "weak spots" becomes a problem. With regard to stability, it is felt that improvement can be obtained by going to thinner walls and by reducing the number of residual impurities.

Hillenbrand commented only briefly on multipacting, stating that it is a problem only for TM cavities and that it can be reduced by the introduction of helium gas into the cavity. Although I needed more illumination of this, Hillenbrand preferred to switch over to a discussion of Nb_3Sn.

Hillenbrand reviewed some of the developments in superconductivity which led to the understanding that the lower critical flux density, B_{c1}, is not the limit for high-field microwave applications, as originally understood. This had led to the consideration of higher transition temperature materials (Type II) for cavity applications, such as Nb_3Sn. By utilizing a material with a high transition temperature, one can operate at a higher temperature, say 4.2 K for Nb_3Sn, simplifying the associated cryogenic equipment and lowering the cost of operation. Hillenbrand also feels that greater stability will be achieved. In addition, the surface resistance of Nb_3Sn will be lower than that for Nb at 4.2 K thus reducing losses. Lastly, the B_c^{ac} for Nb_3Sn is considerably larger than for Nb. There seems to be a whole family of compounds with high transition temperatures (up to 23 K). Siemens has worked with Nb_3Sn simply because it appears to be the easiest to prepare.

One difficulty is caused by the fact that the thermal conductivity of Nb_3Sn is much lower than that of Nb. Therefore, it is mandatory to use Nb_3Sn only in very thin films. However, the film needs to be thick enough so that the field does not penetrate into the Nb core material. Siemens uses evaporation temperatures in excess of 930 C so as to avoid the formation of unwanted phases of Nb_3Sn. The preparation of the cavity is an elaborate process in which many special precautions have to be taken. The basic preparation procedure has been published in the open literature[4,5] so I won't reiterate it here. It seems that after two or three years of experimentation a process has been worked out that yields films with reliable, repeatable properties, but there are some gaps in the understanding of the physics of the situation.

One of the collaborators in this work, Dr. H. Martens, recently passed away. Hillenbrand credited him with many of the important experimental innovations, such as the discovery of the importance of pre-anodization of the cavity before heat treatment. Hillenbrand considers that the anodization procedure (oxypolishing) is the single most important factor in the success that Siemens has had in making high-field, high-Q microwave cavities. He noted that the best results that Siemens has had to date which were a year ago.[4] For Nb_3Sn, the best B_c^{ac} is still 106 mT (at 1.5 K) with Q_0 the order of 10^9. A Q_0 of 9×10^9 was obtained at low magnetic fields. These are compared with the best quoted Nb values at 1.5 K of B_c^{ac} - 159 mT and Q_0 - 3×10^{10}. Siemens has many Nb_3Sn-lined cavities yielding B_c^{ac} in the 80 to 100 mT range with repeatable Q_0s the order of 10^9.

Hillenbrand said that they have found B_c^{ac} to be essentially temperature independent, i.e., it is at least roughly the same at 1.4 and 4.2 K. Also the Nb_3Sn cavities do not deteriorate noticeably after being stored in a dessicator for six months.

Siemens has done fewer experiments with the TM cavity configuration. Their best achievement for Nb_3Sn was quoted as $B_c^{ac} \sim 84$ mT, but most measurements fell around 60 mT. The surface resistance appears to be about the same for both modes.

It is interesting to note that the Nb Sn grains seem to limit out at about 2μ in dia., and 2-3μ in thickness. This size is achieved in 3 hours, at 1050 C. Longer times do not necessarily produce thicker or better films. The amount of material removed by oxypolishing depends upon the voltage used. At 20 volts about 100 Å of film is removed.

Hillenbrand also described a series of measurements of the superconducting energy gap, Δ, for Nb_3Sn up to 10 K. Anomalous values of 1.75 to 2.2 mv were obtained for different samples. It was stated that this might be attributed to the residual presence of a different phase of Sn. Additional work needs to be done to clarify this point. At any rate, Hillenbrand concluded that Nb_3Sn can and will be used successfully in a variety of accelerators and that cavity construction seems straightforward and repeatable enough. Although it was stated that flux densities might be increased by further refining if the preparation procedures. There was no speculation on the ultimately achievable values of B_c^{ac}.

A briefing and laboratory tour was given by Dr. H. Diepers, who developed some of the electropolishing techniques. Some of the cavities designed for use with the Karlsruhe/CERN accelerator were examined. Electropolishing appears to give a quite smooth surface, with roughness averaging around 100 Å. Also important is the fact that electropolishing yields an "undamaged" surface in distinction to some other polishing techniques.

Lastly, I was taken on a tour of Siemens' obvious show pieces, the superconducting transmission line and the levitated "train." This technology has been carried to a rather complete demonstration phase, but now has been shelved because currently, there are simply no customers for it. The superconducting transmission line segment, consisting of a large number of niobium coated aluminum conductors and shields has been demonstrated to carry 10 kA at 110 kV. What is mind-boggling is the comment that an initial charge of 10^5 liters of helium would be required per kilometer of transmission line!

Conclusions

A summary discussion with Gremmelmaier, Pfister, Hillenbrand, and Diepers was held at the end of the day. It was clearly perceived that Siemens' current efforts are focused on the technology needed for the CERN and DESY applications. Their current program is to (1) explore in greater depth TM-cavity designs and measurements, (2) gain improved cavity reproducibility, and (3) find ways of fabricating cavities more cheaply. It seems clear that Siemens has a strong commitment to continue work with Nb_3Sn because of well-known reasons quoted earlier, such as the prospect of operating at a higher temperature. One item of interest is their plan to study a cavity constructed from niobium sheet, rather than milled out of solid block. This would be a more economical approach to cavity construction if good properties can be achieved. My hosts advised that the superconducting cavity program will continue to the end of 1979 at the same level of effort. They are interested in further discussions of American microwave cavity work.

Brief mention was made of a new program at the Technical University of Braunschweig centered about a cavity application at 50 GHz, where dimensional tolerances become quite critical. It is understood that this work will be described at the microwave meeting in Copenhagen next September.

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