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Physicists in Industry (6)

History of Accelerator Technology at Dornier GmbH

Ursula Kaufmann

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The following report narrates the early years of superconducting technologies in accelerator physics. Several sophisticated techniques had to be mastered to achieve a high surface shape fidelity, the best surface polishing quality, and a reliable deposition and ablation of brittle metals to assure high Q factors of large-scale RF cavities. Moreover, it was necessary to reliably manipulate the interior surfaces of the cavities. Our author, Dr. Ursula Kaufmann, gives us a firsthand account of those pioneering days.

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History of Accelerator Technology at Dornier GmbH

Ursula Kaufmann

The Early Years

Since the end of 1970s, Dornier GmbH's Product Division "Satellites and Application Systems" in Friedrichshafen, Germany, has developed and built components for accelerator facilities, such as cryostats, UHV components, couplers, and carbon fiber–reinforced polymer vacuum tubes and RF resonators such as cavities. The activities involved designing and manufacturing self-supporting cavities made of solid normal conducting copper as well as solid superconducting niobium (Nb) for various frequencies from 350 MHz to 3 GHz for accelerator facilities at DESY in Hamburg (D), Research Centers in Jülich (D), Cornell University (USA), and CEBAF (USA) [1], as well as prototypes of Nb-coated copper cavities for CERN in Geneva.

In 1985, I joined Dr. Werner Scherber's team at the Research Division of Dornier System GmbH, a subsidiary of Dornier GmbH, and had the opportunity to collaborate with Dr. Gabriele Arnolds-Mayer to develop niobium-coated copper cavity prototypes for CERN. Gabriele had been recruited by Dornier as an expert in high frequency physics from Wuppertal University, Germany.

Q Factors and Thermal Conductivity

For accelerators with very high end energies, cavities with very high quality factors (about 10^{11}) are required; orders of magnitude above the quality factor feasible with normal conducting materials. This means that the resonator cells must be made of superconducting material instead of normal conducting material. Additionally, the material needs to provide high thermal conductivity because the cavities would have to be cooled by suprafluid liquid helium to keep the cavity shell in a superconductive state. During operation, the RF current in the cavity generates heat, which has to be removed and transported through the cavity shell from the inside of the cavity to the cooling liquid. Superconducting materials, however, have inherently poor thermal conducting properties. Even minimal defects, in particular normal conducting defects such as pinholes of copper in the Nb layer, induce a huge temperature increase in the cavity, limiting the maximum achievable energy or even destroying the cavity.

In addition, the interior surface of the cavity had to be free of defects, such as less than a pinhole in a square meter comparable to a high-quality polished optical laser mirror. The material of choice as superconductor was Nb, having a transition temperature to superconductivity of 9.26 K. The material had to be as pure as possible to provide the required high thermal conductivity and to avoid emission of residual gases dissolved in the sheet material during electron welding of the cavity shells, which could create defects in the weld seams.

Dr. Werner Scherber during a visit to CERN in front of a 4-cell cavity.

Because of the chosen frequency of the accelerator facility, which was 350 MHz for the CERN LEP collider, 4-cell cavity structures were required, which are four cavities connected in series with inlet and outlet tubes at both ends where the particle beam should enter and leave the cavity structure. The length of such a 350 MHz 4-cell cavity structure including the input and output tubes is nearly 2.5 m with a diameter at the cell equators of about 75 cm. However, high-purity Nb is quite soft. As a result, big structures made of high-purity Nb tend to sag because of the material's softness, thus corrupting the required cell structure geometry.

Nb Coating on Copper Surfaces

At that time, a new cell manufacturing process was developed at CERN which combined the high thermal conductivity of oxygen-free copper shells and the superconducting properties of thin, high-purity Nb films deposited thereon. To provide the interior surface of the cavities with the required high-end quality, a chemical polishing process was developed which generated the desired mirror-like surfaces prior to a sputter deposition of a thin Nb film inside the cavity structure. Transferring the cavity from the relatively "dirty" and wet ambient in the chemical treatment step to a clean UHV-vacuum ambience for sputter deposition of Nb onto the interior surfaces posed one big challenge to the manufacturing process. Another obstacle was the chemical treatment itself. The interior geometry of the cavity determines the resonator properties such as the frequency. Therefore, the interior geometry prior to polishing the surface had to include the amount of material removed during the chemical treatment.

1 Continuous Electron Beam Accelerator Facilities in Newport News (VA, USA).

The deposition technique chosen for Nb deposition on the interior surface of the cavity was magnetron sputtering. The cavity serves as vacuum chamber, anode and substrate and a Nb tube inserted in the cavity along its symmetry axis served as cathode. After evacuation to a low base pressure below 10^{-7} mbar, the cavity is filled with high purity Argon (99.9999) to about 10^{-2} mbar.

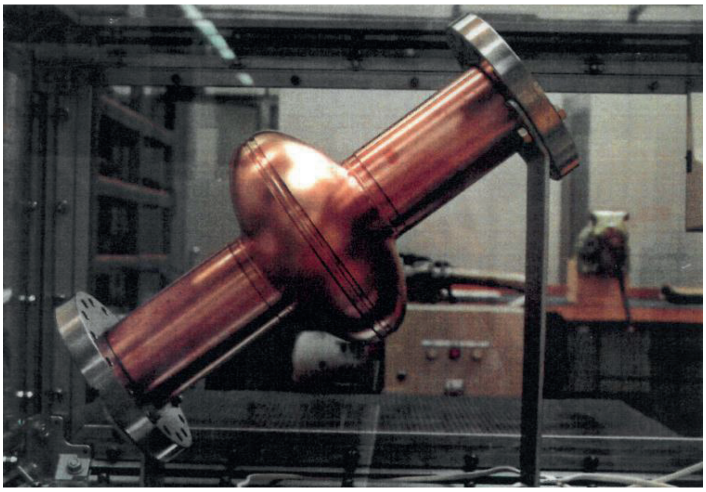
A ring magnet with axial magnetization is inserted into the Nb tube and an electric voltage of a few hundred Volts applied between the cavity and the Nb tube. Ar atoms are ionized as a result of collisions in the vacuum chamber, generating positive Ar ions and electrons. The magnetic field gradient of the ring magnet behind the wall of the Nb tube traps electrons in a narrow volume close to the surface of the Nb tube and more Ar ions are generated by collision ionization in this volume. Ar ions hit the adjacent Nb surface which releases Nb atoms so that a very high deposition rate can be achieved on the copper surface close to the magnet position, improving the purity of the growing Nb coating. First, the inlet/outlet tubes are coated one after the other by placing the magnet in the Nb tube in a corresponding position and then the magnet is moved into the center of the cavity. Deposition of about 1 μm of Nb in the cavity center took about 30 min. Then, the cavity is vented with air and ready for inspection.

The chemical polishing mixture inside the cavity removed copper from the interior surface as long as it was in contact with the surface. Discharging the mixture at the end of the process needed some time, and copper removal was still occurring on those surface areas which were still in contact with the chemical polishing mixture, while the process had already stopped in areas where the mixture had already been drained off.

Therefore, one of the first problems we had to solve in our development was providing the interior cavity surface treatment with a well-defined start and stop in the polishing procedure.

Special Electrochemical Polishing Technology

For pragmatic reasons, we started the whole development process on a smaller 1.5 GHz cavity instead of a 350 MHz cell, which could be more easily handled. We chose electrochemical polishing for treating the cavity, as we have dealt with the subject in another project. The electrochemical polishing fluid was inert as long as no electrical voltage was applied to the electrodes, that is, the cavity shell and a counterelectrode inside the cavity, and the reaction time could be controlled by switching the voltage on and off. Because of the elliptical shape of the cavity, some effort was put in the design of a counterelectrode inside the cavity to allow for homogeneous material removal during electrochemical polishing. The counterelectrode had to be inserted and removed through the inlet/outlet tube and nevertheless had to at least have a constant approximate distance to the interior surface of the cavity shell. As a result, the electrode turned out to be an umbrella-like module (which could be expanded



inside the cavity after insertion and collapsed before removal to an appropriate diameter).

After the polishing step, the cavity was thoroughly rinsed with ultrapure water, dried with inert gas, and transported into a clean room ambient. There, the cavity was opened and a hollow Nb tube inserted as cathode for magnetron sputtering. After a short sputter cleaning step of the copper surface, a magnet was shifted inside the Nb tube during sputtering where the location of the magnet determined the location of the plasma plume and hence the location of material deposition onto the interior surface of the inlet tube, cavity, and outlet tube. A few 1.5 GHz cells had been prepared that way.

The coated cavities fulfilled the requirements nicely, and the technique could be successfully transferred to single-cell 350 MHz cavities and even a 4-cell cavity structure. Optical inspection of the cavities polished and coated with the described process revealed high-quality surfaces.

In the end, CERN decided to use sputter-coated cavities in the LEP accelerator facility.

Ursula Kaufmann (born in 1957 in Ludwigshafen/Rhein, Germany) studied physics at Karlsruhe Technical University and received her doctoral degree in 1984 for her work on tunneling spectroscopy on superconducting Nb_3Sn at the Karlsruhe Research Center. She was a postdoc at IBM Research Laboratory in Rüschlikon, Switzerland, 1984–1985. From 1985 to 1991, she worked with Dornier System GmbH in Friedrichshafen, Germany, on prototype development of superconducting Nb-coated copper RF cavities, as well as on Josephson devices and ceramic superconductors. In 1991, she joined the Research Laboratory of Daimler AG in Ulm and worked on molecular beam epitaxy of ceramic superconductors. From 1994 to 2003, she worked in the patent department of Daimler AG in Frankfurt and Stuttgart. Since 2003, she has been in private practice as a German and European patent attorney in Stuttgart.