EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-ISR-VA/81-34

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A MINIATURE SCANNING ELECTRON MICROSCOPE FOR INVESTIGATION OF THE INTERIOR
SURFACE OF A SUPERCONDUCTING Nb RADIOFREQUENCY ACCELERATING CAVITY

by

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Geneva, December 1981

1. INTRODUCTION

At CERN the design of the Large Electron Positron storage ring (LEP)¹⁾ involves normal conducting accelerating radiofrequency cavities giving beam energies up to ~ 90 GeV. To increase this energy to 130 GeV, superconducting Nb cavities have been proposed¹⁾, a solution which would also offer substantial power saving at lower energies compared to conventional copper cavities.

For the feasibility studies a 500 MHz single cell cavity was made by spinning and electron beam welding from 2 mm Nb sheet. The form and dimensions of the cavity are shown in Fig. 1.

In such cavities one of the main limitations to performance is non resonant electron loading from field emitted electrons which produces frequency detuning, input impedance variations and absorption of radiofrequency power all which tend to reduce the maximum electric field gradient in the cavity. In addition, point-like areas of increased resistivity may lead to a fast radiofrequency breakdown, i.e. quench, at high fields.

To reach a better understanding of these and other phenomena a temperature mapping system using a chain of 39 carbon resistors moving around the outer wall of the cavity was developed²⁾. With this system any internal point-like heat source appearing during cavity operation could be localized with an accuracy of ± 3 mm.

All significant loss areas in the cavity will be shown on such a temperature map an example of which is shown in Fig. 2. On the x axis is plotted the distance in cm along a circle of constant latitude. The y axis gives the number of the carbon resistor and the vertical axis displays the temperature increase measured by each resistor.

On Fig. 2 three distinct hot spots are seen. However, correlation of these hot spots with internal surface features was difficult due to the relative inaccessibility of the interior wall. For this reason it was proposed to install in the cavity at room temperature a miniature scanning electron microscope to be able to identify with as high resolution as possible these lossy spots located previously with the temperature mapping system.

2. SCANNING ELECTRON GUN

There was available on the market (RIBER SA, model CER 410) a scanning electron gun with a beam diameter of 1 μm whose dimensions (250 mm length, 56.5 mm diameter) were such that it could be introduced into the cavity and with a suitable support system 'see' most of the interior surface.

The primary electron beam energy was variable up to 10 keV with beam currents of up to 1 μA . The secondary electron detector was a channeltron electron multiplier mounted on the nose of the gun and looking at the scanned area (see Fig. 3). To obtain an image the output from this channeltron was used to modulate the intensity on a TV monitor in synchronism with the rastered primary electron beam as in conventional scanning electron microscopes.

With the nose of the gun about 30 mm from the scanned surface an area at least $20 \times 20 \text{ mm}^2$ could be scanned to search for gross features, but at reduced primary beam energy (2.0 keV), and hence reduced resolution. This is, of course, no disadvantage since the beam energy may be increased, the scan amplitude decreased and the focus adjusted to 'zoom in' on something of interest with high resolution and magnification without moving the scanning gun. Magnifications from 3 x to 500 x were possible. The area 'seen' by the scanning electron gun could be very easily located on the outside to within $\pm 2 \text{ mm}$ by simply moving a lightly magnetized pointed instrument across the outer surface and noting the position which gave maximum distortion of the image due to deflection of the primary electron beam.

Electrical connections to the gun were by teflon insulated Cu wire and to the outside via standard ultrahigh vacuum electrical feedthroughs with a maximum voltage rating of 12 kV.

3. MECHANICAL SUPPORT SYSTEM

In Fig. 3 is shown a schematic diagram of the scanning electron gun with channeltron mounted in the Nb cavity.

To cover the interior of the cavity rotation about two axes is necessary, $\pm 70^\circ$ about a horizontal axis (A) and 360° about a vertical axis (B). The first movement (A) was accomplished using a standard ultrahigh vacuum rotary motion feedthrough coupled via a system of stainless steel universal joints and ultrahigh vacuum compatible bearings to a stainless steel worm and bronze wheel gear mechanism.

For both economy and simplicity the second rotation (B) was made possible using a normal axial thrust bearing outside the vacuum. The vacuum sealing was by means of a pair of differentially pumped elastomer lip seals.

Due to the length of the electron gun a third movement (C) was necessary to be able to scan both the upper and lower parts of the cavity. This movement was by means of bellows and the cavity was held in position against the atmospheric axial forces by means of an adjustable table fixed to the bottom of the cavity and to a rigid framework which surrounded the whole assembly.

Apart from the bronze gear wheel all parts were made in either 316 L+N stainless steel or aluminium alloy.

An actual photograph of the scanning electron gun plus channeltron mounted on the mechanical support system is shown in Fig. 4. The teflon covered probe projecting in front of the electron gun is a recent addition and will be used for in situ field emission measurements.

4. VACUUM SYSTEM

All materials in the vacuum were ultrahigh vacuum compatible with the exception of the elastomer lip seals and 10 viton O-rings.

The system was pumped by a 270 ls^{-1} turbomolecular pump and a liquid N_2 cooled titanium sublimation pump. Base pressures $\sim 5 \times 10^{-9}$ torr were obtained after two days of pumping.

5. CAVITY PREPARATION

After electron beam welding the cavity was chemically polished in a mixture of HF , H_3PO_4 and HNO_3 to remove about $20 \text{ }\mu\text{m}$ from the surface, rinsed in demineralized water, then immersed for 10 minutes in $\text{H}_2\text{O} + \text{H}_2\text{O}_2$ and finally rinsed in filtered dust free methanol.

6. RESULTS AND CONCLUSIONS

A first examination of the cavity interior with the scanning gun revealed a wealth of detail. The objects and surface structures observed could be classified into four distinct groups:

- (a) macroscopic defects such as scratches, tool marks, dents, etc. made during manufacture of the cavity;

- (b) small insulating surface objects $\sim 1 \mu$ which charge up, deflect the primary electron beam and are hence difficult if not impossible to 'see';
- (c) circular spots where some liquid drop had obviously dried leaving a residue;
- (d) three types of badly conducting dust lightly attached to the surface, filaments, fibres and particles - all three of which could be seen to move under the charging influence of the scanning electron beam.

It must be emphasized that the dust was only seen at the first examination and by careful and rapid mounting of the scanning system in the cavity in a filtered laminar air flow it was almost completely eliminated.

Examples of surface structures of types a), b) and c) are shown in Figs. 5, 6 and 7 respectively.

If we refer to the temperature map of Fig. 2 we can see that there are three obvious hot spots at resistance (R) numbers R 14, R 25 and R 30. The electron micrographs of the corresponding interior surfaces are shown in Figs. 8 and 9 for R 14 and R 30 there being no obvious internal surface structure at the hot spot indicated by R 25.

The R 14 structure was about 100μ in diameter, appeared to project from the Nb surface and was slightly insulating. Unfortunately, neither the angle of incidence of the primary electron beam nor the direction of the channeltron could be varied to give a better perspective of surface structures. The normal chemically polished cavity surface may be seen in the background.

The hot spot detected by R 30 was a collection of small insulating objects barely visible at high magnification due to charging effects. These objects covered an area $\sim 10 \text{ mm}$ in diameter. The apparent multiple hot spots above R 30 detected at R 29 and R 28, this direction being up, are due to convection in the liquid He.

An attempt was made to remove both objects for analysis by manual excision using a sharp, tungsten carbide-tipped tool. Subsequent analysis in a conventional scanning electron microscope equipped with a dispersive x-ray analysis system revealed traces of Fe at R 30 and Cu and Fe at R 14. The origin of these elements is at present obscure but they may have originated during forming of the cavity.

Fig. 10 shows the state of the Nb surface at R 14 after this scraping, where the burrs at the end of each scrape mark are clearly visible. It was felt that such projections might be detrimental to cavity operation so both areas were ground with a small tungsten carbide grinding wheel. After this grinding operation the cavity was immersed in HCl then rinsed in the $H_2O + H_2O_2$ mixture.

Subsequent cavity operation revealed that the R 30 hot spot had indeed been removed but that at R 14 was worse. In Fig. 11 is shown a mosaic of the area of R 14 where the effect of the grinding is clearly visible. However, some of the burrs have been missed and it is these that are thought to have been the cause of the losses at R 14.

A similar investigation of the R 30 area showed that the grinding had indeed removed all traces of burrs and that the resulting relatively rough surface was in fact satisfactory as far as cavity operation was concerned.

With the scanning electron gun no internal surface features were observed which could conclusively be correlated with the field emitting electron sources.

Once these lossy areas have been located with the scanning electron gun, the obvious question is what is their composition? If a scanning Auger system using a cylindrical mirror analyzer and high resolution concentric scanning electron gun could be made compact enough to fit into the Nb cavity, then the elemental composition could easily be obtained.

Alternatively, if the characteristic x-rays from the hot spot stimulated by the 10 kV electrons of the scanning gun could be analyzed using a small solid state detector, this would also give information about the composition.

However, the x-ray production rate is low at 10 keV and it is doubtful if a solid state detector with sufficient resolution and sensitivity is available. The additional complication of cooling the detector to cryogenic temperature is difficult but not impossible.

In conclusion it has been shown that the scanning electron gun system and the temperature mapping device are complementary tools in the investigation of lossy areas in superconducting Nb cavities. The hot spots are localized by the temperature scanner and subsequently 'looked at' with the scanning electron gun.

ACKNOWLEDGEMENTS

The authors are indebted to Ph. Bernard, R. Calder, N. Hilleret, A. Insomby, H. Lengeler, H. Piel, J. Tuckmantel and W. Weingarten for support and many useful discussions.

REFERENCES

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2. Ph. Bernard et al., Proc. of the 11th Int. Conf. on High Energy Accelerators Geneva, (1980), 878.

FIGURE CAPTIONS

1. The 500 MHz Nb single cell cavity - all dimensions in mm.
2. A temperature map of the Nb cavity at 2.32 K and an accelerating electric field of 0.99 MV m^{-1} .
3. A schematic cutaway diagram of the scanning electron gun with channeltron mounted in the Nb cavity.
4. An actual photograph of the scanning electron gun with channeltron mounted on the support mechanism.
5. A typical macroscopic defect - a scratch - on the internal cavity surface.
6. A small insulating surface object giving rise to a black spot.
7. A round spot reminiscent of the residue from a dried liquid drop.
8. The scanning electron micrograph of the hot spot detected by resistance R 14.
9. The scanning electron micrograph of the hot spot detected by resistance R 30.
10. The Nb surface at R 14 after scraping with a tungsten carbide-tipped tool.
11. A mosaic of the area around R 14 showing the effect of grinding and the burrs from the scraping still untouched.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

— 50 μ

FIGURE 8

500 μ m

FIGURE 5

1 mm

FIGURE 6

50 μ

FIGURE 7

FIGURE 9

1 mm

1 mm

FIGURE 10

2 mm

FIGURE 11