NONDISTRUCTIVE TESTING INSTRUMENT OF DISHED Nb SHEETS FOR SRF CAVITIES BASED ON SQUID TECHNOLOGY

Q.-S. Shu, J. Susta, G. F. Cheng, I. Phipps, AMAC International Inc., Newport News, VA 23606
R. Selim, J. Mast, Christopher Newport University, Newport News, VA 23606
P. Kneisel, G. Myneni, Jefferson National Lab, Newport News, VA 23606.
I. Ben-Zvi Brookhaven National Lab, Brookhaven, NY 11719.

Abstract

The performance of superconducting RF cavities used in accelerators can be enhanced by detecting micro particles and inclusions which are the most serious source of performance degradation. These defects prevent the cavities from reaching the highest possible accelerating fields. We have developed a SQUID scanning system based on eddy current technique that allows the scanning of curved Nb samples. This SQUID scanning system successfully located Tantalum defects about 100 μm diameter in a flat Nb sample and was able to also locate the defects in a cylindrical surface sample. Most importantly, however, the system successfully located the defects on the backside of the flat sample and curved sample, both 3-mm thick. This system can be used for the inspection and detection of such defects during SRF cavity manufacturing.

INTRODUCTION

Superconducting RF (SRF) accelerators have been developed using a few cavities or several hundreds of cavities, such as those at Cornell, Argonne, TJNAF-CEBAF, CERN and DESY. The accelerating gradients of about 35MV/m have been reached in several TESLA 9-cell cavities at DESY. Major technical efforts are focused on overcoming the most serious obstacles, field emission (FE) and thermal breakdown (TB), which prevent SRF cavities from reaching the theoretical performance limits (40-50 MV/m for Nb cavities). A few small metallic inclusions per cavity, such as Tantalum, could already lead to a substantial reduction in the projected maximum electric field strength of the cavities [1]. In the manufacturing processes of niobium cavities, the normal method is to fabricate half-cells from flat niobium sheets, and weld them into a multi-cell cavity. The forming process to make the half-cells can introduce new inclusions into the Niobium sheets which cannot be detected during the final quality control steps. The Superconducting Quantum Interference Device (SQUID) system that we developed is a scanning system that uses eddy current technique to detect impurities in curved niobium surfaces. Previously developed instruments can scan flat sheets, but no development was pursued to scan curved surfaces [2,3]. SQUIDs are the most sensitive detector of magnetic flux and have unparalleled sensitivity, bandwidth and femto-tesla field resolution.

Eddy current techniques that use conventional magnetic sensors have the disadvantage of using high frequencies that are useful in detecting surface defects. Eddy current systems that use SQUID sensors have the advantage of using low frequencies for the excitation currents, which allows the system to find flaws deep in the material [4]. This can be explained by the fact that the generated eddy current is in general at the surface of the material and penetrates the material only down to small distance defined as the skin depth or the penetration depth. The penetration depth depends on the conductivity of the material as well as the frequency of the excitation current [5,6]. The use of low frequency has its own challenges since the current density will also decrease with increased depth and the signal from the deep defect will attenuate as it has to travel through the material before reaching the sensor.

TECHNICAL APPROACH

The use of SQUID sensors in nondestructive evaluation (NDE), specifically for detecting defects in metals has been well documented [4, 5]. In particular, eddy current techniques have been used in DC SQUID systems to image defects deep under the surface using relatively low frequencies. The use of an improved DC SQUID system for detecting Ta inclusion in NB sheets and cavities will enhance the capabilities of the system in terms of increased sensitivity and spatial resolution.

The general rules for detection resolution are:

- Resolution (the minimum separation between two magnetic features) is dependent on both the distance from the detection coil to the sample (liftoff), and the size of the detection coil.
  - If the sensor very close to the sample (< 2 coil diameters), then the coil size is the limiting factor to resolution.
  - Spatial resolution δ can be expressed approximately as: Coil Diameter / (10-20)
  - The better the Signal/Noise ratio, the better the resolution
- Because the flux sensitivity of SQUID sensors is roughly constant (for a given type of SQUID sensor), there is an inverse relationship between sensitivity of detecting a field B and spatial resolutions. BN δ2 ~ 10-14 T mm2

Needle flux transformers can have higher spatial resolutions, but limited B_N

- Scan time is also important. The higher the resolution, the longer it takes to scan a certain surface.

We have demonstrated that our DC low temperature SQUID system is capable of scanning flat NB samples and detect defects at the surface, inside the material or on the back side of the Nb sheets [6]. The system consists of a liquid Helium dewar, a SQUID probe and iMAG SQUID controller built by Tristan Technologies (San Diego, CA.) based on the specifications of our team. The SQUID output is connected to Stanford Research SR530 lock-in amplifier to isolate the signal produced from the induced current. The lock-in amplifier produces an in-phase signal (Ø = 0) and a quadrature signal (Ø = 90). The system includes a 3-d motion controller that controls the motion of the sample under the tail of the dewar. The computer controls the motion system through a National Instruments PCI-7344 Motion Controller PC card. A Motor driver by National Instruments (MID-7604) powers a three-axis setup: x, y, for translation, z for elevation.

The experiment is fully automated using LabVIEW software that allows the computer to interface with all the components of the system. The computer would allow the user to set the scanning step size (usually 1mm), parameters of the SQUID controller and the settings for the lock in amplifier. Figure 1, below, presents a schematic diagram of the SQUID setup that is used to scan Nb flat samples. The system operates by moving the sample below the pickup coil. After the sample is moved one step, a measurement by the SQUID is activated after a short settle time. Therefore, in our data, one pixel represents a scanned area of 1 mm^2. Each file produced in scanning a sample contains two sets of data: in-phase X (0), and quadrature X (90).

EXPERIMENTAL DETAILS

The SQUID Nondestructive Testing (NDT) system used in our set up has a probe with a pick up coil that is configured as a dBz/dz gradiometer to cancel the effect of uniform magnetic fields from the environment. To increase the spatial resolution the pickup coil is required to be as small as possible. The pickup coil with our system has a diameter of 2 mm, the smallest possible with wire winding technology. We have used a planar current inducer to produce a more uniform eddy current pattern in the sample, making it easier to initially “zero off” the SQUID signal when no defect is present [7]. The system includes a 3¬D motion controller which moves the sample. The current inducer is mounted on the bottom of the Dewar, as shown in the schematic diagram of Fig.1. We have modified the scanning system to allow for scanning curved samples. by adding a fourth motor for the rotation of curved samples.

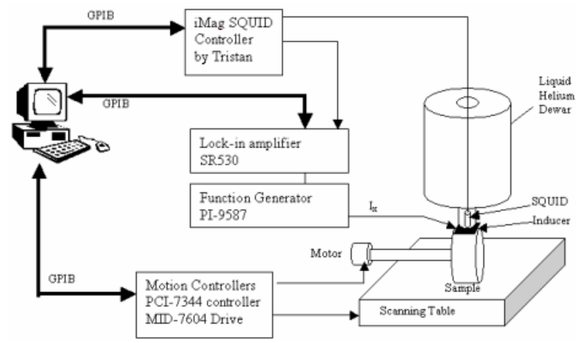

Figure 1: Schematic diagram of the SQUID system

The DC Low Temperature Superconductor (LTS) SQUID system includes a gradiometer probe and a non-magnetic liquid He dewar. The LTS type SQUID is selected for its higher field sensitivity (~ 50 X 10^{-15} Tesla). The SQUID gradiometer uses two coils wound in opposite directions that are configured as dB_z /dz gradiometer to cancel the effect of uniform magnetic fields as shown schematically in Fig.2. As a result, the SQUID gradiometer has the advantage of being able to be used in a non-magnetically shielded environment. The signal detected by the SQUID system is due to the net flux caused by the non-uniform magnetic field generated by the eddy current near the defect.

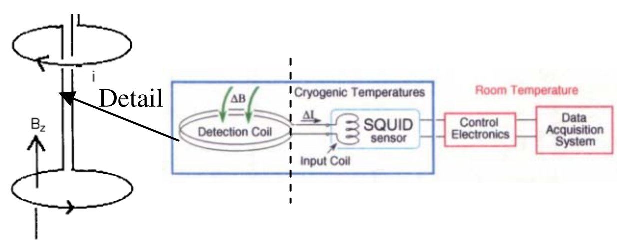

Figure 2: Gradiometer SQUID schematic

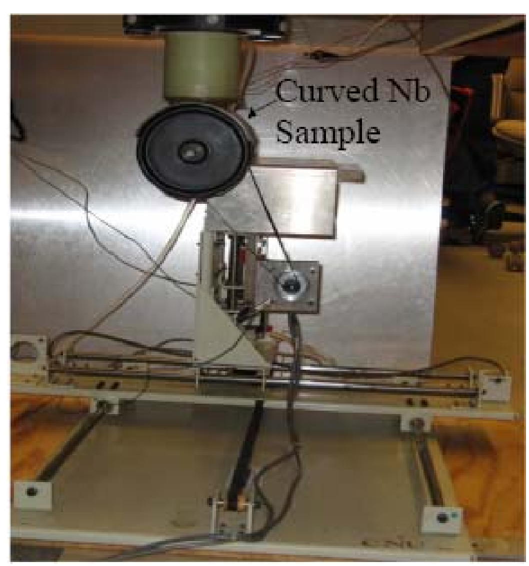

Figure 3: The curved sample set up shown under the tail of the Dewar.

Figure 3 shows the modified system for detecting defects in curved sheets. The experiment is fully automated using a LabVIEW based program that allows the user set the scanning step size (usually 1mm), parameters of the SQUID controller and the settings for the lock in amplifier.

RESULTS

For this investigation, several samples were made to test the feasibility of our SQUID-based NDT system for detection of Nb defects in general, and SRF cavities in particular.

1) Flat Nb sheet with Ta defects.

The sample was made by punching small holes into 11 cm x 23 cm Nb sheet and tantalum grains were placed into the holes. The filled holes were then welded over with an electron beam. Signatures from some defects near surface scans are difficult to distinguish due to interface with signals related to the surface topography. To take advantage of the SQUID low frequency capabilities and to maximize the signal from the defects in this scan, the sample was scanned with the defects on the bottom surface (back side). The plot in Fig. 4 is one such scan, where the frequency of the excitation current is 20.5 kHz. The figure shows a plot of three defects: # 4 (100µm x 150µm), # 5 (100µm in diameter) and # 6 (200µm x 150µm). The graph shows typical signature from each defect including peaks (max.) and troughs (min.) identifying the location of the defect. One notices that the location of the peaks and troughs is affected by the depth of the defect. Defects 4 and 6 are within 100µm of the surface while defect 5 is located more than 200µm below the surface. As a result of this depth profile, the signature of defect # 5 is flipped compared to the other two signals of defects 4 and 6.

2) Large Flat Nb sheet with Ta defects.

The second flat sample used in this project was provided by the DESY group. This sample is fabricated in a similar fashion as our flat sample by placing tantalum into holes and melting niobium over the inclusion. Figure 4 shows a 3-D plot of a surface scan of defect # 5 of this sample, which has a diameter of 150µm and is located at a depth of 474µm. The frequency used in this scan is 20.63 kHz. The sample was then scanned with the defects on the bottom (back side) of the Nb sheets. This resembles the scanning of the inside surface of Nb half-cell, where the pick up coil of the SQUID is further away from the defects. Figure 5 shows inclusions # 1 and # 2, the smallest defects in the DESY sample. Inclusion # 1 has a diameter of 120 microns and inclusion # 2 has a diameter of 140 microns. Inclusion number # 2 is clearly identified by a strong signature and a signature from inclusion 1 is located at the top right of the plot. Once again this clearly shows that our system can detect defects in the 100 µm range.

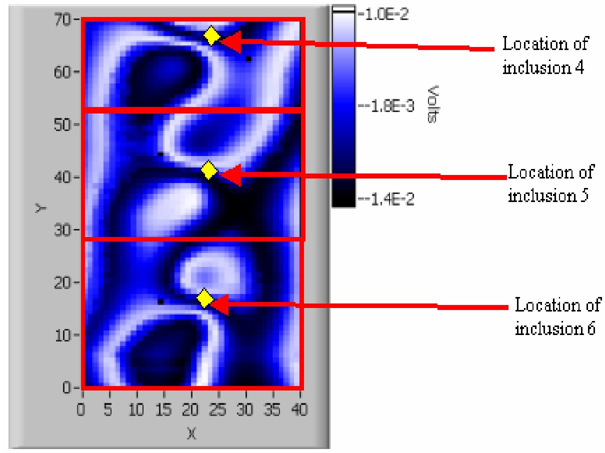

Figure 4: Intensity plots of defects 4, 5 and 6 in a flat Nb sheet

3) Nb Half-Cylinder with Ta defects on both sides.

The third sample in this study is a niobium half cylinder as shown in the schematic in Fig. 6 a. The radius of the half cylinder is 5 inches and the length 5 ½ inches. Defects were placed both beneath the surface of the outside surface of the sample as well as on the interior surface of the sample. The defects consist of tantalum inclusions produced in the same manner as those of the flat samples. The curved sample posed more challenges than the flat samples. Fig. 6 b shows the results of a surface scan of defect # 8 on the outside surface of the curved sample using an excitation frequency of 20 K Hz. Defect # 8 has dimension of 100µm x 120µm and is 150µm below the surface. Clearly the trough and the peak in the graph indicate that our system can detect surface defects in curved sample.

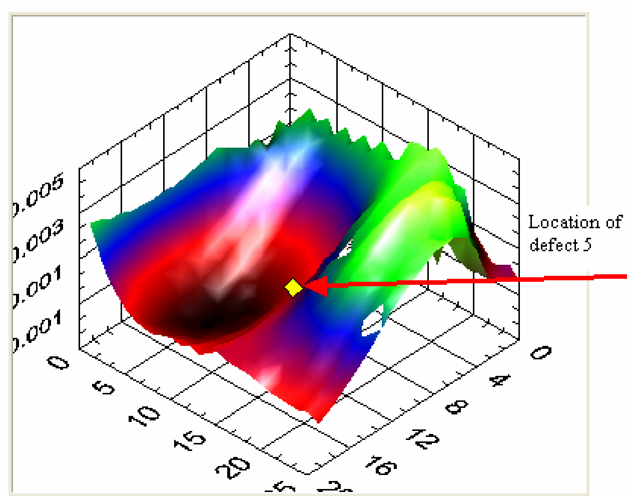

Figure 5: 3-D plot of scan of defect # 5 in DESY sample

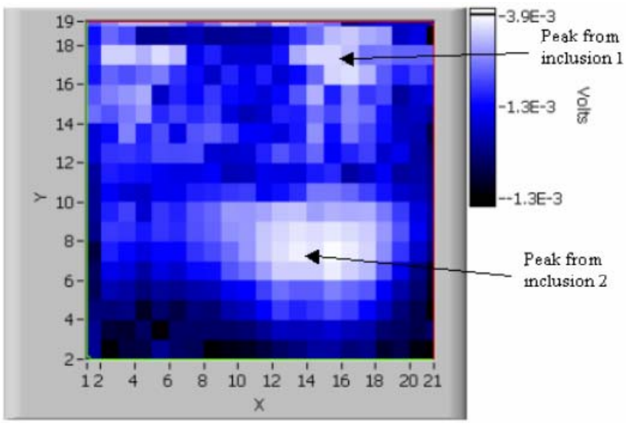

Figure 6: Deep scan of defect #1 and #2, the smallest defects in the DESY sample.

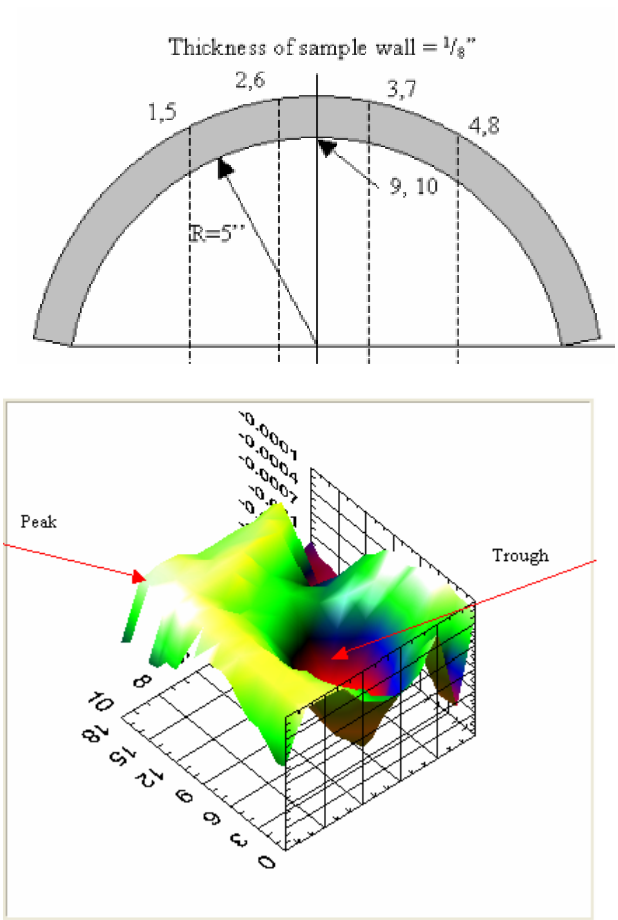

Figure 7: a) Schematic diagram of the Nb half-cylinder sample with known defects. b) 3-D intensity plot of a scan of defect #8.

Finally, figure 7 shows a scan of defect number 10, which is located on the inside surface of the half-cylinder sample. It has a diameter of 220 microns and is located 500 micron above the inside surface. This filtered data clearly demonstrate that the system is capable of scanning deep (~ 2.5 mm from the top surface) into this curved sample and identify Ta defects.

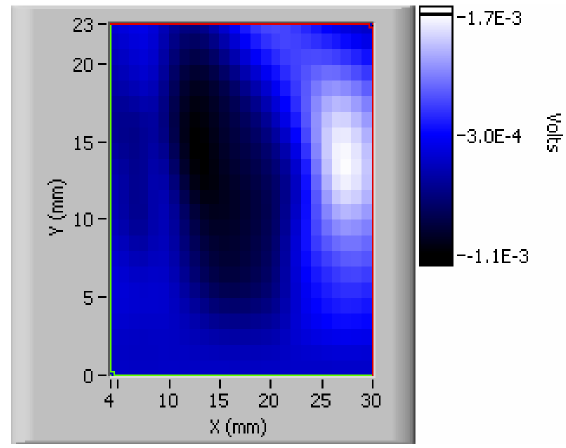

Figure 8: Intensity plot of defect #10 on the inside surface of the Nb half cylinder sample.

FURTHER IMPROVEMENT

1. Improve spatial resolution to detect 25 μm Ta inclusions.

We propose to replace the detection pick up coil used in the SQUID system, which has a diameter of 2mm, with a 1mm diameter coil. This first order gradiometer pick up coil is expected to increase the sensitivity of detection by a factor of two or more thus enabling us to detect defects in Nb sheets that are smaller than 25 microns. Further development of the data analysis software will enhance the features and the detection of defects that are smaller than 25 microns (see #3 below).

2. Increase speed of scanning system.

We are planning to run the scanning system in a continuous mode without stopping before each data collection point. Since the bandwidth of the closed flux loop (SQUID electronics) is 50 KHz and the frequency of the excitation current is 20 KHz or less, we can run the scanning system in a continuous fashion and collect data at a rate of 100 points/sec. This is a conservative rate of collecting data and can be increased if we need to decrease the total scanning time. By setting the scanning speed to a constant value, we will be able to scan a 30 cm long line in 3 seconds and collect data at 1mm interval using this rate of 100 points /sec. A 30 cm X 30 cm Nb sheet can be scanned in 900 seconds or 15 minutes. Using the 2-SQUID sensor system, we will be able to scan the same 30cmX30cm sheet in half the time i.e. in 7.5 minutes.

3. Enhance the data analysis software.

The data analysis software that we developed allows us to vary the phase using the in-phase and quadrature data sets collected for each sample. This enables us to maximize the signal produced by the defects based on their depth and as a result to better detect defects at various depths. We propose to add two more features to this data analysis software:

1) Add a band pass filter that allows us to filter high frequency noise, which allows us to smooth the detected features of the signal. We can also correct the lift off effects by carefully choosing the low frequency cut off for this filter. This added filter will effectively enhance the detection of smaller defects especially the ones below 50 microns.
2) Add a final signal processing procedure that allows us to "flatten" or quiet the background level of the data set and as a result enhance the features of the defects. This final step will increase our ability to inspect and identify the defects when examining the whole data file.

CONCLUSION

We have successfully developed a SQUID based scanning system for detecting defects in flat and curved Nb sheets. We have successfully detected defects that are 100 µm in diameter. The results of this work show that for the first time a curved Nb surface can be scanned to detect Ta inclusions on the back surface through a ~ 2.5 mm thick sheet. This allows for the possibility of using this DC SQUID eddy current system in detecting and locating any Ta inclusions that are on the inside surface of a SRF half cell.

In phase II the system will be capable of scanning a 30cm x 30cm Nb sheets and detecting Ta defects smaller than 25 microns in less than 10 minutes. The system will be further optimized, the sensitivity will be improved, and the software will be enhanced so that an innovative 3-D SQUID based equipment for testing Nb sheets will be prototyped for DOE laboratory applications & commercialization.

REFERENCES

[1] Singer W, Brinkmann A, Proch D, Singer X, Physica C, 386 P. 379-384 (2003).
[2] P. Bauer et al., "Eddy Current Scanner Operating Instructions", Fermilab collaboration Note TD-04-029, August 2004.
[3] C. Welzel, M. Korn, M. Mück, F. Schölz,; A. Farr,, Paper 5ED03, Applied Superconductivity Conference, Jacksonville, Oct. (2004).
[4] Jenks W G, Sadeghi S S H, Wikswo J P, J. Phys. D, 30 P. 293-323 (1997).
[5] Ma Y P, Wikswo J P, Review of Progress in QNDE, eds. Thomas D O, Chimenti D E, Vol. 17, P. 1067-74, Plenum Press, New York, NY (1998)
[6] Y.P. Ma and J.P. Wikswo Jr., Review of Progress in QNDE 13, P. 303-309 (1994).
[7] Selim R, McFarlane M, Mast J, Wincheski B, Simpson J., Review of Progress in Quantitative Nondestructive Evaluation, eds. Thomas D O, Chimenti D E, Vol. 24, P. 1638, Plenum Press, New York, NY (2005).