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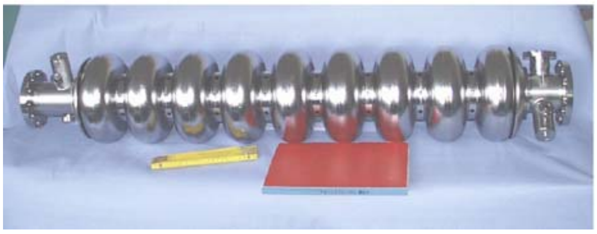

MAGNETIC FIELD SENSORS APPLIED TO ELECTROPOLISHING OF SUPERCONDUCTING RF CAVITIES

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In this work an electromagnetic non invasive and contact-less technique using Flux-Gate 1st order electrical gradiometer is proposed to detect the magnetic field distribution during electropolishing of copper surface. Local information regarding the dissolved copper surface during the electropolishing process has been obtained. The electropolishing of the copper surface employed in superconducting RF cavities has been monitored using magnetic field sensors. An electromagnetic inversion of the magnetic field imaging have been implemented to better understand the effect of the cathode geometry on the electropolishing process.

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Abstract

In this work an electromagnetic non invasive and contact-less technique using Flux-Gate 1st order electrical gradiometer is proposed to detect the magnetic field distribution during electropolishing of copper surface. Local information regarding the dissolved copper surface during the electropolishing process has been obtained. The electropolishing of the copper surface employed in superconducting RF cavities has been monitored using magnetic field sensors. An electromagnetic inversion of the magnetic field imaging have been implemented to better understand the effect of the cathode geometry on the electropolishing process.

INTRODUCTION

To improve the technology of superconducting rf cavities increasing the accelerating energies and saving the power dissipation, Niobium thin film is sputtered on the inner cavity copper surface. This approach offers a considerably higher stability against quenching, insensitivity to small magnetic fields and a higher quality factor than that of bulk Niobium at working temperature (4.2-4.5 K). In order to obtain the required performance in a superconducting RF cavity, such as high acceleration gradient with low power losses, an extremely high quality Nb superconducting surface is required.

The Nb surface quality plays an important role in the rf cavities performance. In fact, some limitations could be rise from defects or scratches on the Nb surface. The latter could produce thermal instability due to a niobium particle with bad thermal contact to the copper surface or a Niobium tip, where the field enhancement leads to a breakdown of superconductivity. Moreover, field emissions could take place because the high surface electric fields lead to electron emission from scratches or particles located on the surface via electron tunneling. This process dissipates power and therefore can cause an exponential decrease of the quality factor with the accelerating field. Since the Nb thin film is deposited by using a magnetron sputtering to avoid any contaminations and defects of the Nb film, the copper surface preparation before Nb coating represents a crucial step in the fabrication process of RF cavities. For this reason the quality control of the copper surface requires an ongoing monitoring of the process by a suitable technique. Most conventional electrochemical tests needs that reference or standard electrodes be introduced in the solution to obtain a measurement of the potentials, but this necessarily perturbs the system. An alternative technique is represented by the measurements of the I-V characteristic of the electrochemical cell. An alternative technique is represented by the measurements of the I-V characteristic of the cell. This method allows to control the process of not easily accessible cavity shape, but doesn't give spatial information on the electropolishing copper surface. To overcome this limitation electromagnetic technique based on magnetic sensors could be considered. The advantage due to the application of the magnetic field monitoring respect to the current-voltage technique concerns the possibility to obtain a local information, in a non invasive way, of the ongoing polishing process over the copper surface even when its shape could be very complex.

In order to achieve the ongoing monitoring of the quality control of the copper surface, it is necessary to choose the most suitable sensor considering its magnetic field sensitivity, spatial resolution and the frequency bandwidth. Examples of magnetic sensors that can be applied in electromagnetic inspections are Flux Gate, Hall probe, GMR (Giant-Magneto Resistance), and low and high temperature SQUIDs (Superconducting QUantum Interference Device) that represent the most sensitive but also the most expensive sensors. Instead the other mentioned device works at room temperature and are cheaper than SQUIDs. The Flux-Gate magnetometers have a higher magnetic field sensitivity (10 pT/√Hz at 1Hz) than the Hall probes and the GMR. The latter is a emerging magnetic sensor that potentially could be more sensitive than Flux-Gate [1]. The last two type of sensors generally are characterized by a sensitivity less than 1 μT, a good spatial resolution less than 100 μm, and a wide frequency bandwidth (300-400 kHz).

The aim of this work is to show how the magnetometry can be a suitable and useful diagnostic technique to perform the quality control of the materials employed in the RF cavities fabrication. In this paper the electromagnetic techniques based on magnetic sensors used for the quality control of RF cavities have been reported. Static and dynamic measurement of the in plane magnetic field component during the electropolishing of the Copper surface, using a Flux-Gate electronic gradiometer, has been carried out. Moreover, an electromagnetic inversion of the magnetic field distribution based on Fast Fourier Transform (FFT) has been performed to calculate the current density distribution due to the electropolishing process. The knowledge of the current density distribution allows to

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obtain information about the electrochemical activity respect to the cathode geometry.

EXPERIMENTAL METHODS

In this work the electropolishing of copper surface with different geometries has been monitored. The electrolytic cells are shown in figure 1.

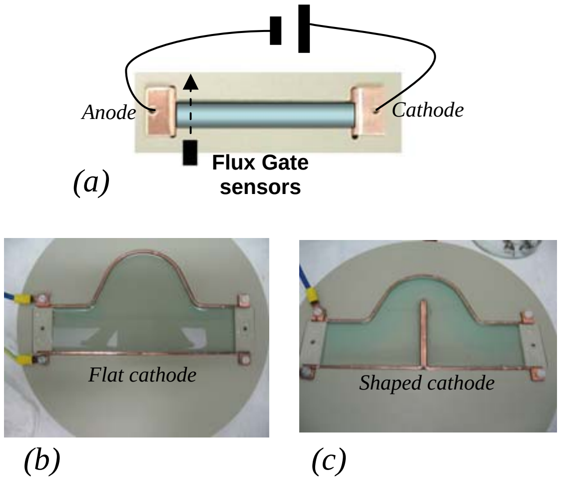


Figure 1 : The electrolytic cells monotored. (a) rectangular cell, (b) and (c) cavity like-shape with flat and shaped cathode, respectively.

Cells with rectangular electrodes (figure 1(a)) of different width: 8 mm, 16 mm and 24 mm, and cells characterized by iris-like anode and flat or shaped cathodes (figure 1(b) and 1(c), respectively) have been tested. The electrolytic solution was 55% Phosphoric acid and 45% n-buthanol, During the electropolishing process that was driving in voltage, the Flux-Gate 1st order electronic gradiometer measured the in-plane component of the magnetic field gradient, G_x, due to the current distribution between the two electrodes.

A magnetic imaging of ongoing electropolishing process have been carried out moving the sensors over the cells area(within the electrodes), with a speed of 3mm/s and a continuous acquisition mode with 6 data points/mm. In both cells geometry (rectangular and cavities shape) the magnetic field imaging is represented by a matrix in which the columns are the line scans obtained moving the Flux-Gate 1st order electronic gradiometer from the anode to the cathode. To monitor the electropolishing process of copper surface Flux-Gate sensors have been applied because of their capability to detect the magnetic field produced in the electropolishing process. The Flux-Gate sensor is a solid state device based on the non linearity of the magnetic characteristic of its sensing ferromagnetic core. It can measure the d.c or the low frequency a.c. magnetic field component, with a field sensitivity ranging from 10^{-11} to 10^{-4} Tesla. A flux-Gate sensor is made of a high permeability cylindrical core around which there are two coaxial coils: bias coil and sensing coil. This sensor detect directly variation of the magnetic field generally using a Phase Sensitive Detection (PSD), in this way it can work in a bandwidth ranging from d.c. to 5 kHz.

FLUX GATE MAGNETOMETRY APPLIED TO THE ELECTROPOLISHING OF COPPER

It was already demonstrated [2] that it is possible to control the electrolytic polishing of metal, following the magnetic polarization curve. The experimental measurements were carried out driving the cell in voltage and positioning the Flux-Gate sensors above the electrodes (cathode or anode).

Increasing the current value, the magnetic field versus the voltage is monitored. In this way the H-V polarization curve can be obtained.

Comparing the H-V and I-V polarization curves (Figure 2) it is possible to identify the three different regions that characterized the process: pitting (α), polishing (β) and the gas evolution (γ).

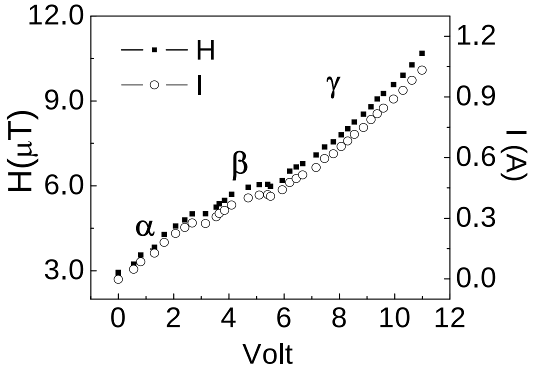


Figure 2 :H-V and I-V polarization curve.

This result means that to have information about the electropolishing process, magnetic measurements with contactless sensors are reliable as such as the current measurement. The advantage of magnetic measurements is due to the possibility to control the electropolishing process without intrusive probes, independently of the shape and dimension of the cell surface. Moreover, using the magnetic field the best working point and polishing condition can be achieved.

During the electrolytic process there is a flow of ions from the anode to the cathode that produce a corresponding magnetic field, which can be monitored by the Flux-Gate sensors. Using the magnetic field produced by the ions a very simple model can be applied to evaluate the anode oxidation. If every ion is approximated by a charge **q** with a speed **v,** the produced magnetic field at distance **r** can be represented as follow:

$$\vec{B} = \frac{\mu_0}{4\pi} q \frac{\vec{v} \times \vec{r}}{\vec{r}^3} \qquad (1)$$

where μ_0 (4π x 10^{-7} Tm/A) is the permeability of the free space. Since the Flux-Gate sensors measure the in-plane component of the field B_x, produced by the current $\mathbf{j}_y$ orthogonal to the electrode, the module of magnetic field becomes:

$$B_x = \frac{\mu_0}{4\pi} q \frac{v}{r^2} \tag{2}$$

the speed **v** can be obtained considering that the current density **j** is **j = Nqv**, where **N** is the number of ions per volume **N=n/V** (m^{-3}). Then the magnetic field can be written as

$$B_x = \frac{\mu_0}{4\pi} \frac{jSl}{nr^2} \tag{3}$$

from this equation it is possible to obtain the number of ions **n,** that start from the anode and go in the solution:

$$n = \frac{\mu_0}{4\pi} \frac{jSl}{B_x r^2} \tag{4}$$

Using the Faraday law,

$$w = \frac{jStM}{nF} \tag{5}$$

where **w** is the dissolved copper at the anode, ***S*** is the cross section of the cell, ***t*** is the time during the measurement, **M (**63.456 g/mole) is the copper atomic mass and **F (**96500 As/mole) is the Faraday constant. Considering the equation (4) the Faraday law can be written as

$$w = \frac{4\pi B_x M r^2 t}{\mu_0 l F} \tag{6}$$

which can be used to calculate the corrosion rate **w/t**.

This simplified model has been used to estimate the dissolved copper of the anode, for cells with length of 50 mm and different width (8 mm, 16 mm, 24 mm) using a static measurement of the magnetic field across the anode.

Table 2: corrosion rate and dissolved copper at 4V

Cell width [mm]	**w**[g] at 4V by balance	**w**[g] at 4V by B_x
8	0,012±10^{-4}	0,011±7E-3
16	0,023±10^{-4}	0,020±7E-3
24	0,05±10^{-4}	0,032±7E-3

Table 3: corrosion rate and dissolved copper at 7V

Cell width (mm)	**w**[g] at 7V by balance	**w**[g] at 7V by B_x
8	0,025±10^{-4}	0,048±7E-3
16	0,035±10^{-4}	0,020±7E-3
24	0,13±10^{-4}	0,035±7E-3

The data reported in table 2 and 3 indicates the dissolved copper (w) at the anode in 5 minutes in correspondence of the plateau (4V) and at 7V, respectively.

The data calculated using the simple model previously described has been compared with the results obtained weighing the electrode after the magnetic measurement by means of a balance with a sensitivity of 10^{-4}g. It could be noted that in the plateau (4V) the difference between the results of the two different techniques are quite similar, the difference is less than 2%. For a voltage of 7V, instead, the compared data show a difference higher than 2%, probably because of the more chaotic corrosion process due to the gas evaporation. In this case the in-plane component of the magnetic field is not capable to describe the quantitatively the copper dissolution.

ELECTROMAGNETIC INVERSION OF MAGNETIC FIELD IMAGING

Dynamic measurements, moving the magnetic sensors above the cells, monitored the magnetic field distribution due to the flow of current in the solution.

In figure 3 is reported the magnetic imaging of the rectangular cell, at the potential of 4V.

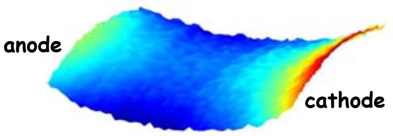


Figure 3: magnetic field distribution of the rectangular cells at the potential of 4 V.

It is not very simple to extrapolate information about the corrosion process from the magnetic field distribution. For this reason it is necessary to invert the magnetic field distribution to represent the corresponding current distribution which reflects the electrochemical activity in the cell.

In general, the inverse magnetic problem does not have an unique solution but in the case of two dimensions it can be solved uniquely. To obtain the current density distribution during the copper electropolishing of the rectangular cells, the mathematical technique based on the Fast Fourier Transform (FFT) has been applied. The magnetic inverse technique applied in this work to the electropolishing process of rectangular cells has been used successfully in other applications and it is described in detail [3] by B. J. Roth et al.

To calculate the current density from the magnetic field data the rectangular cell has been approximated to a finite short dipole, which generates a magnetic field expressed by Biot-Savart law:

$$B(r) = \frac{\mu_0}{4\pi} \int \frac{J(r') \times (r - r')}{|r - r'|^3} d^3 r'$$

where *J* is the current density that produce the field and *r* the distance where the magnetic field is measured. The configuration of the Flux-Gate sensors allows to measure only the in-plane component of the magnetic field, in this case B_y, so the previous expression becomes:

$$B_y(x,y,z)=\frac{\mu_0}{4\pi}l\cdot z\cdot\iint\frac{J_x(x',y')}{\left[(x-x')^2+z^2\right]^{3/2}}dx'dy' \qquad (8)$$

In the formula above *l* and *z* are the length of the cell and the distance between the probe and current source, respectively. It could be noted that measuring the y component of the magnetic field, B_y, it is possible to obtain only the corresponding *x* component of the current density, J_x. Moreover, the equation (8) represents the convolution between the current density *J* and Green function *G*, expressed by:

$$G(x-x',y-y',z)=\frac{\mu_0}{4\pi}l\cdot z\cdot\frac{1}{\left[(x-x')^2+z^2\right]^{3/2}} \qquad (9)$$

By using the convolution theorem it is possible to rewrite the equation (8) in the Fourier space as:

$$b_y(k_x,k_y,z)=g(k_x,k_y,z)\cdot j_x(k_x,k_y)$$

where the $b_x(k_x,k_y,z)$, $j_x(k_x,k_y)$ and $g(k_x,k_y,z)$ are the two dimensional Fourier transforms of the magnetic field , the current density and the Green's function, respectively. The variables k_x and k_y are the components of the spatial frequency K. Then the current density in the Fourier space is given dividing the magnetic field by the Green's function:

$$j_x(k_x,k_y)=\frac{b_y(k_x,k_y,z)}{g(k_x,k_y,z)}$$

Finally, the current density distribution J_x is due by the inverse Fourier transformer of the j_x.
In figure 4 the imaging of the current distributions obtained applying the FFT technique to the corresponding magnetic field data (figure 3) is shown. It could be noted that the current distribution is uniform along the total length of the cell, because the plateau of the polarization curve (at 4V) guarantees an uniform corrosion.

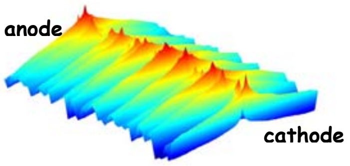
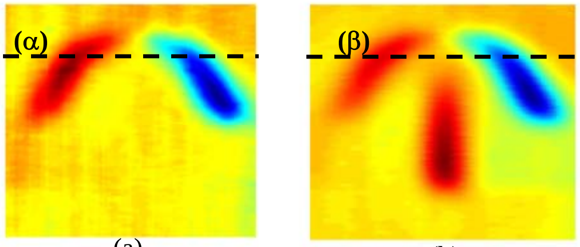


Figure 4: the current distribution for the rectangular cells at the potential of 4 V.

Starting from this results about a very simple cell geometry another electrode configuration very similar to the shape of the RF superconducting cavities has been analyzed.



(a) (b)

Figure 5: Magnetic field distribution for the cells with different cathode shapes: flat (a) and curve (b).

Considering the two different cathode geometry, flat and shaped (figure 1 (b) and (c)), a magnetic imaging of the cells have been carried out. The magnetic field maps are shown in figure 5. The magnetic field images distinguish successfully the different electropolishing activity due to the different cathode shape. Moreover, further information about the efficiency of the electropolishing process, due to the two cathode geometry, can be obtaining considering the current distribution. Applying the FFT technique, using as Green's function the equation:

$$G(x-x',y-y',z)=\frac{\mu_0}{4\pi}l\cdot z\cdot\left[\frac{1}{\left[(x+x')^2+z^2\right]^{3/2}}-\frac{1}{\left[(x-x')^2+z^2\right]^{3/2}}\right]$$

the current distribution across the anodes has been calculated. In figure 6 the comparison between the current distribution, related to the lines scan (α) and (β)in the magnetic field imaging of figure 5, is reported.

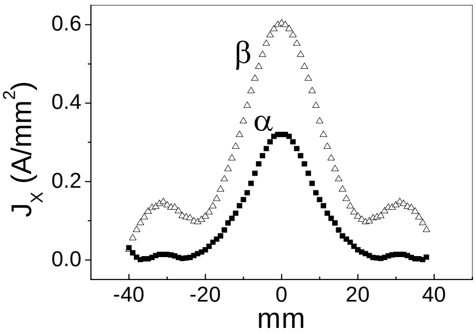


Figure 6: Comparison of the corresponding current density for lines scan extracted from the magnetic maps of fig 4. (α) flat cathode and (β) shaped cathode.

The experimental results demonstrate that the current intensity in the case of shaped cathode (β) is higher than the corresponding current in the cell with flat cathode. In other words the shaped cathode assures a more current across the anode curvature as a consequence a more efficient electropolishing of the surface is obtained. This result is confirmed by the visual inspection of the cells. In figure 7 the pictures of the cells with the two cathode geometry are reported.

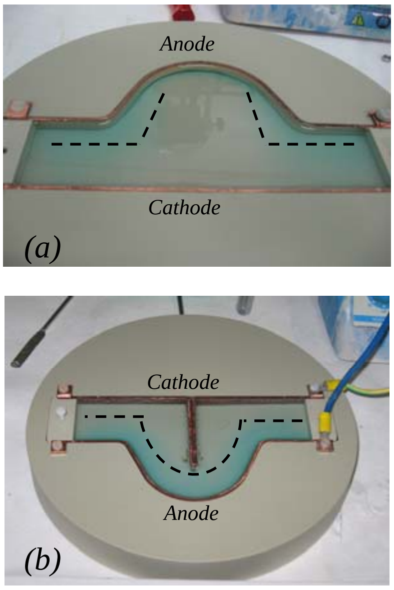


Figure 7: pictures of the flat (a) and shaped (b) cathode during the electropolishing process. The dot lines confine the viscous layer due to uniform electropolishing process.

These pictures are related to the voltage of 4V, where the corrosion process is uniform. The dot lines confine the viscous layer (the blue area across the anode) that enables the uniform electropolishing of the copper surface. As can been noted in the case of flat cathode the viscous layer is very thin in correspondence of the iris, while using the shaped cathode the viscous layer is present along all the anode surface with the same intensity.

CONCLUSIONS

The ongoing corrosion during the electropolishing of copper metals surface by static and dynamic measurements using a first order Flux-Gate electronic gradiometer has been monitored. An estimation of the copper dissolution can be obtained using a model based on the Faraday law and using the magnetic field measurement. Moreover, a magnetic inversion algorithm on a 2D cavity mock-up has been carried out successfully to obtain the current distribution on the copper surface. This result has been demonstrated that the shaped cathode allows a more uniform electropolishing process in geometry of the RF superconducting cavities. Moreover, the results demonstrate that the suggested technique is useful to improve the quality process of the electropolishing of copper surface for the fabrication of RF superconductive cavities.

REFERENCES

[1] J.K. Spong et al. "Giant Magnetoresistive Spin Valve Bridge Sensor," IEEE Trans Magn, Vol. 32: p. 366-371, 1996, see also: J. Deak et al." A low noise fluxgate single domain" App. Phys. Lett. 8, p. 1157-1159, 1996.

[2] C.Bonavolontà, F.Laviano, V.Palmieri, M.Valentino "Application of flux-gate magnetometry to electropolishing" proceeding of RF superconductivity Lubecca (Germany), 2003.

[3] B. J. Roth, N. J. Sepulveda, J. P. Wikswo Jr, "Using a megnetometer to image a two-dimensional current distribution", J.Appl.Phys 65, 1989, p. 361-372.