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Fermi National Accelerator Laboratory
Technical Division / Development & Test Dept.
PO Box 500 MS 343
Batavia, IL 60510
FAX : 630-840-8032

FIONDA (Filtering Images Of Niobium Disks Application)
Filter application for Eddy Current Scanner Data analysis

C. Boffo, P. Bauer
Fermilab, Technical Division.

1. INTRODUCTION

As part of the material QC process, each Niobium disk from which a superconducting RF cavity is built must undergo an eddy current scan [1]. This process allows to discover embedded defects in the material that are not visible to the naked eye because too small or under the surface. Moreover, during the production process of SC cavities the outer layer of Nb is removed via chemical or electro-chemical etching, thus it is important to evaluate the quality of the sub-surface layer (in the order of 100nm) where superconductivity will happen.

The reference eddy current scanning machine is operated at DESY; at Fermilab we are using the SNS eddy current scanner on loan, courtesy of SNS. In the past year, several upgrades were implemented aiming at raising the SNS machine performance to that of the DESY reference machine [2]. As part of this effort an algorithm that enables the filtering of the results of the scans and thus improves the resolution of the process was developed. The description of the algorithm and of the software used to filter the scan results is presented in this note.

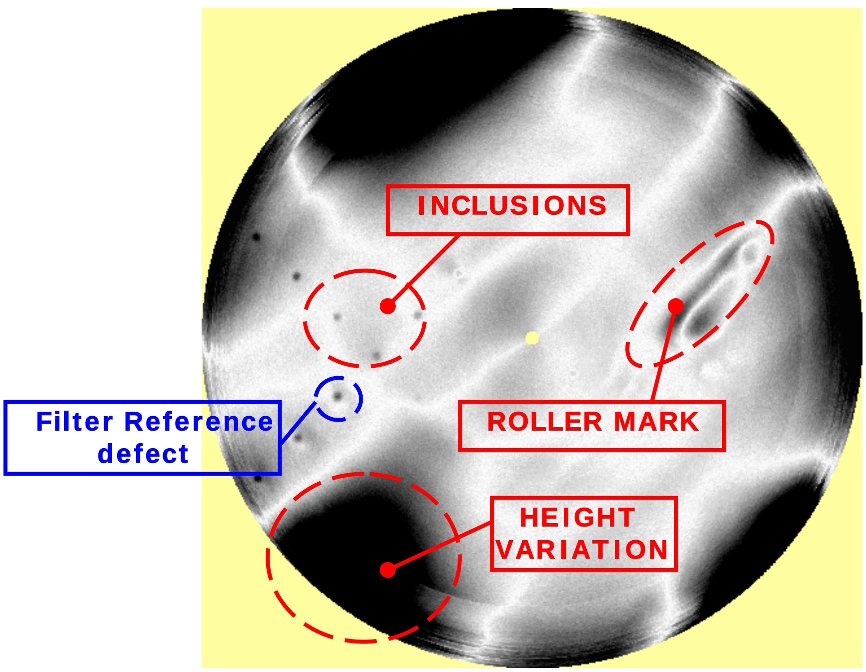

Figure 1 Result of an eddy current scan of the DESY Niobium calibration disk obtained at Fermilab with the SNS scanner using Niobscan (the provided data acquisition and analysis software) with highlights of typical features.

2. DATA PROCESSING

The result of an eddy current scan(imaginary part) is shown above in Figure 1. Shown is the result obtained from the low frequency (990 kHz) channel. A second set of data is simultaneously recorded on an high frequency channel. The picture shows in gray scale the signal obtained during the scan, mapped over the surface of the inspected area. Since the probe is moving in radial direction while the table is rotating with the sample fixed to it, the scanned area is disk shaped. A more detailed explanation of the scanning process can be found in [3].

The Niobscan software provided by the manufacturer is used both for data acquisition and for data analysis. Once the scan is finished one can choose to plot the data in Cartesian or polar coordinates and use a scaling function to adjust the gray scale of the full image to correct the contrast and highlight the defects. This function can be applied to a specific area to improve the contrast. A filter function which takes into account the fact that the probe is detecting signals over a small area not over each single point of the surface of the material is also available. Furthermore the real or imaginary part of the signals from different channels can be added, subtracted and scaled to maximize the defect to background ratio.

Additional enhancements of the results can be obtained using standard image processing software which allow to sharpen the picture or to adjust the hue and saturation of colors. The biggest limitation of these tools is that one does not operate on the data themselves but on their representation, additionally the number of points saved during a scan is much higher with respect to what can displayed on the screen of a computer. Moreover there is no direct correlation between the parameters changed through the image processing software and the type of topology on the surface that one wants to enhance or eliminate.

Being able to directly access the data collected during the scan is the best path toward a more powerful analysis of the results of a scan.

3. NSD FILE TOPOLOGY

The scan results are displayed by Niobscan on the screen of the PC and can be saved in two formats: Bitmap image (BMP) and NSD custom format. Working on the bitmap image implies the same limitations than working on the images themselves using an image processing software. The optimal path to enhance the scan results is reading the NSD file directly.

This file contains the full information about the scanning parameters and the scan results themselves in hexadecimal format. The map of the file is described in the Niobscan user manual. This file is divided into three areas:

- Header
- Body
- Optional features

3.1. Header

The header contains the scanning parameters like the rotation speed, the number of points per turn, the number of lines per millimeter, the probe settings and many others. All these numbers are stored in different formats and must be decoded using the correct data types in order to obtain the content.

3.2. Body

The body contains the scan data as a sequence of short data type: every scanner reading consists of four numbers representing the real and imaginary part of each of the two scanning channels.

3.3. Optional Features

This section contains the scaling factor applied by Niobscan to the scan results in order to obtain the correct representation on the screen with a 256 gray scale.

4. FILTER DESIGN

The decoding process in the filter application described here is performed using MatLab by reading the hexadecimal file sequentially, extracting the useful information and skipping the non interesting data. The results are saved in two temporary MatLab files (.mat), one for the header and the other for the body.
Once the data of the scan are available in a file, one can organize them in a matrix where the rows correspond to a full rotation of the sample and the columns correspond to the angular increments. Since there are two channels and each channel is defined by a complex number, each data point, in principle, is composed by four numbers; however, as result of a specific calibration procedure, the defects in the material are usually identified using the imaginary part of the low frequency channel. Therefore the matrix only contains this number as data point.
Since the number of data points acquired per circumference is fixed for all radii one obtains a full matrix. Given this matrix structure, the image available in Niobscan (shown in Fig. 1) can be regarded as a series of rows (circumferential lines) or as series of columns (radial lines) as shown in Figure 2.

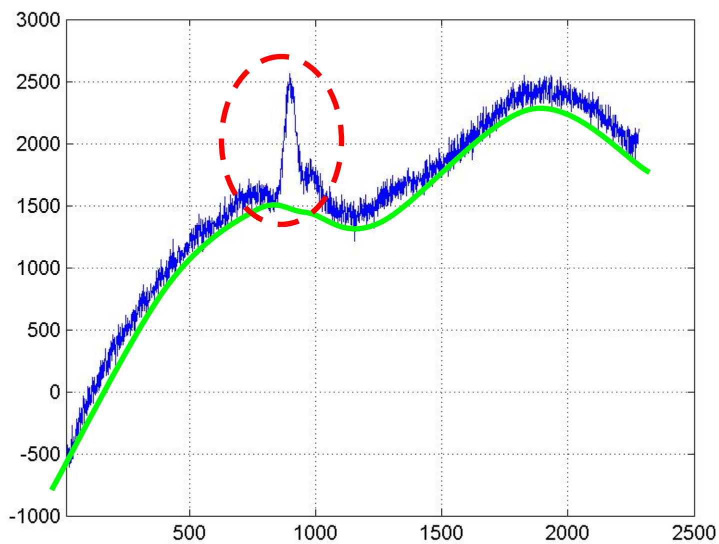

Figure 2 Line representation of scanned data along a radius (columns)

Fig. 2 shows the radial san data through the “filter reference defect” in Fig. 1. The major problem of the scan results, such as shown in Fig. 2, is that features like the one highlighted in red, which correspond to possible inclusions (defects) in the Nb, can be hidden in images like Fig. 1 by the long wave features (green curve in Fig. 2) related to long range thickness variations of the sample. For example the data shown in Figure 2 present a vertical bandwidth of 3000 arbitrary units while in reality we are interested in the spike highlighted in red with a height of ~1000 arbitrary units. The consequence is that the 256 grayscale used for the image representation is spread in the 3000 range losing 2/3 of the total sensitivity.
Assuming that Fig.2 is a typical result of the scan, the best approach to enhance the defect would be to eliminate both the low and high frequency “noise” by applying a band pass FIR filter like the one shown in Fig.3. Assuming that 1Hz corresponds to a wave with full period equal to the line length, a pass band filter of 10-500 Hz was found to be the optimal choice.

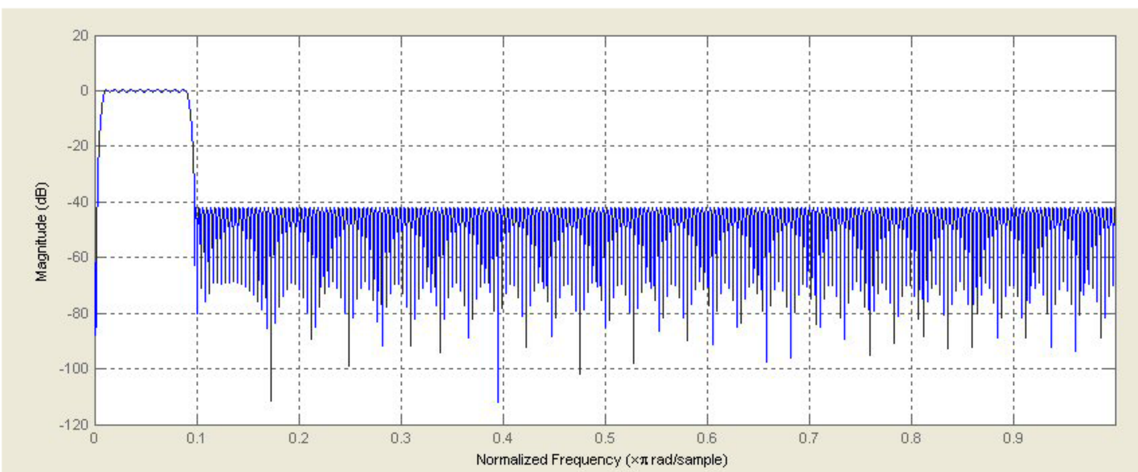

Figure 3 FIR filter magnitude response

The filter parameters have been optimized, given the number of points per line, using the data filter toolbox in MatLab. The filter can be applied to both the radial and circumferential directions to obtain a flatter surface from which the defects show up as sharp peaks as displayed in Figure 4.
At this point one can represent the matrix as a 3D image where the X and Y represent the rows and columns of the matrix itself while the intensity in proportional to the value of each element of the matrix as shown in Figure 5.

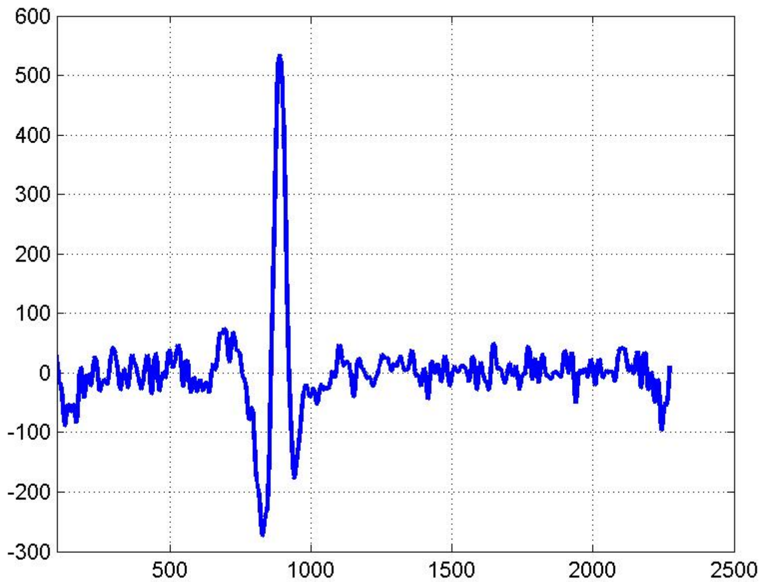

Figure 4 Signal as from Fig. 2 after the FIR filter is applied

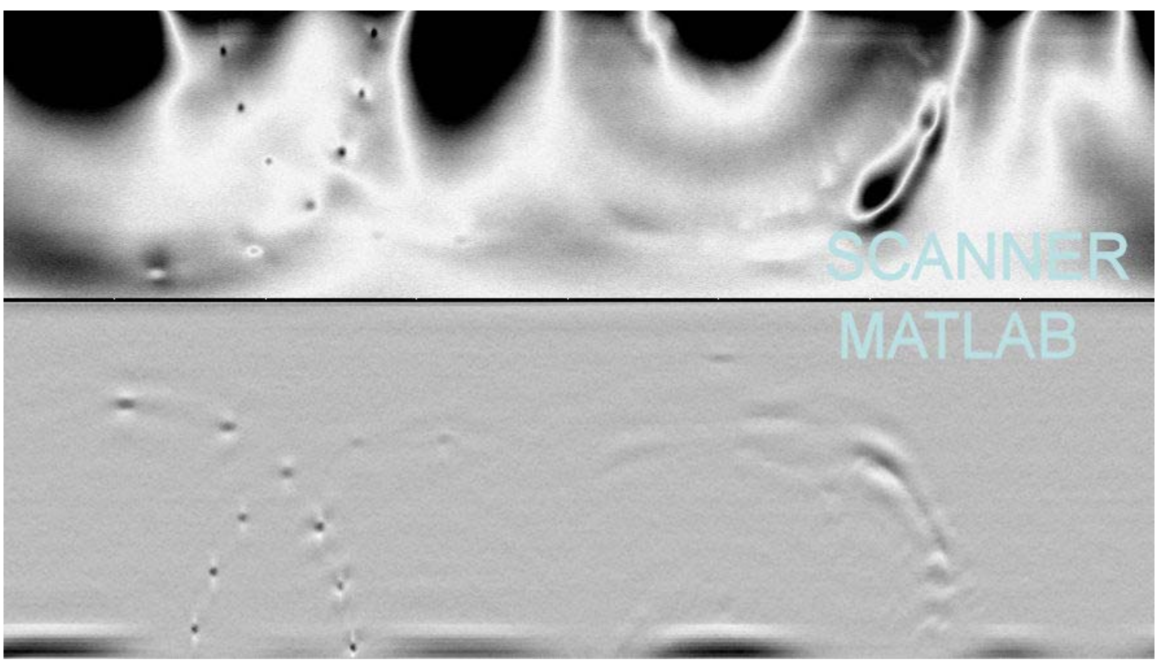

Figure 5 polar representation of scanned disk before and after filtering

5. ADDITIONAL DATA HANDLING

Additional operations can be performed to enhance further the results.

For each single line one can calculate the mean value of the signal and its standard deviation. In order to reduce the background noise one can attenuate by a factor 100 all the signals within the standard deviation value, results are shown in Fig. 6.

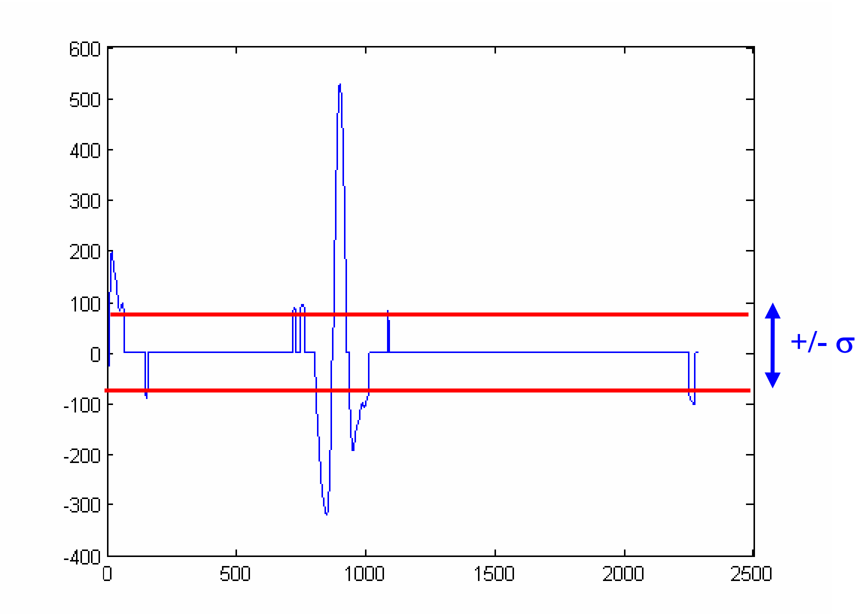

Figure 6 filter result from Fig. 5 after reducing the background

Additionally one can decide to plot the square of the signal in order to highlight the peaks corresponding to defects in the materials.
Since the best representation of the data is still an image of the scanned surface, one can apply a polar coordinate transformation to represent the data of the matrix with the correct dimensions and shape of the scanned material as shown in Fig. 7.

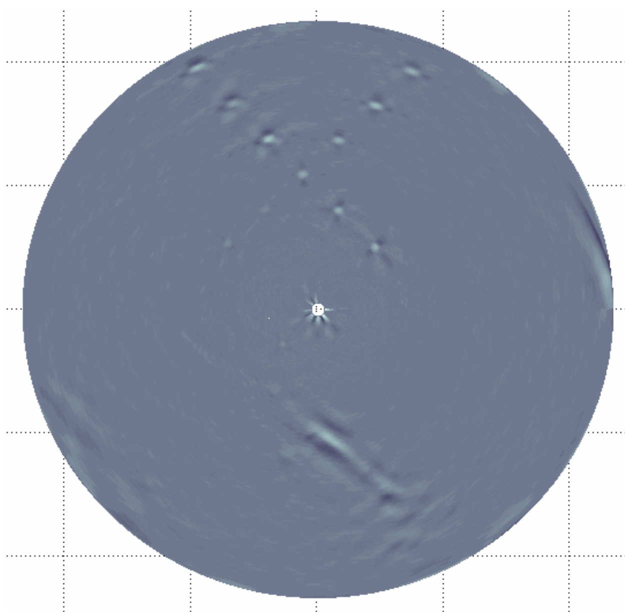

Figure 7 Scan result after filtering

Finally a line with a standard defect was attached to the bottom of the matrix (which corresponds to the innermost circumferential signal). This addition, invisible to the operator, allows the normalization of the images color scale.

6. RESULTS

The following pictures show the comparison between the standard representation of the scan results and the filter application results in two interesting cases:

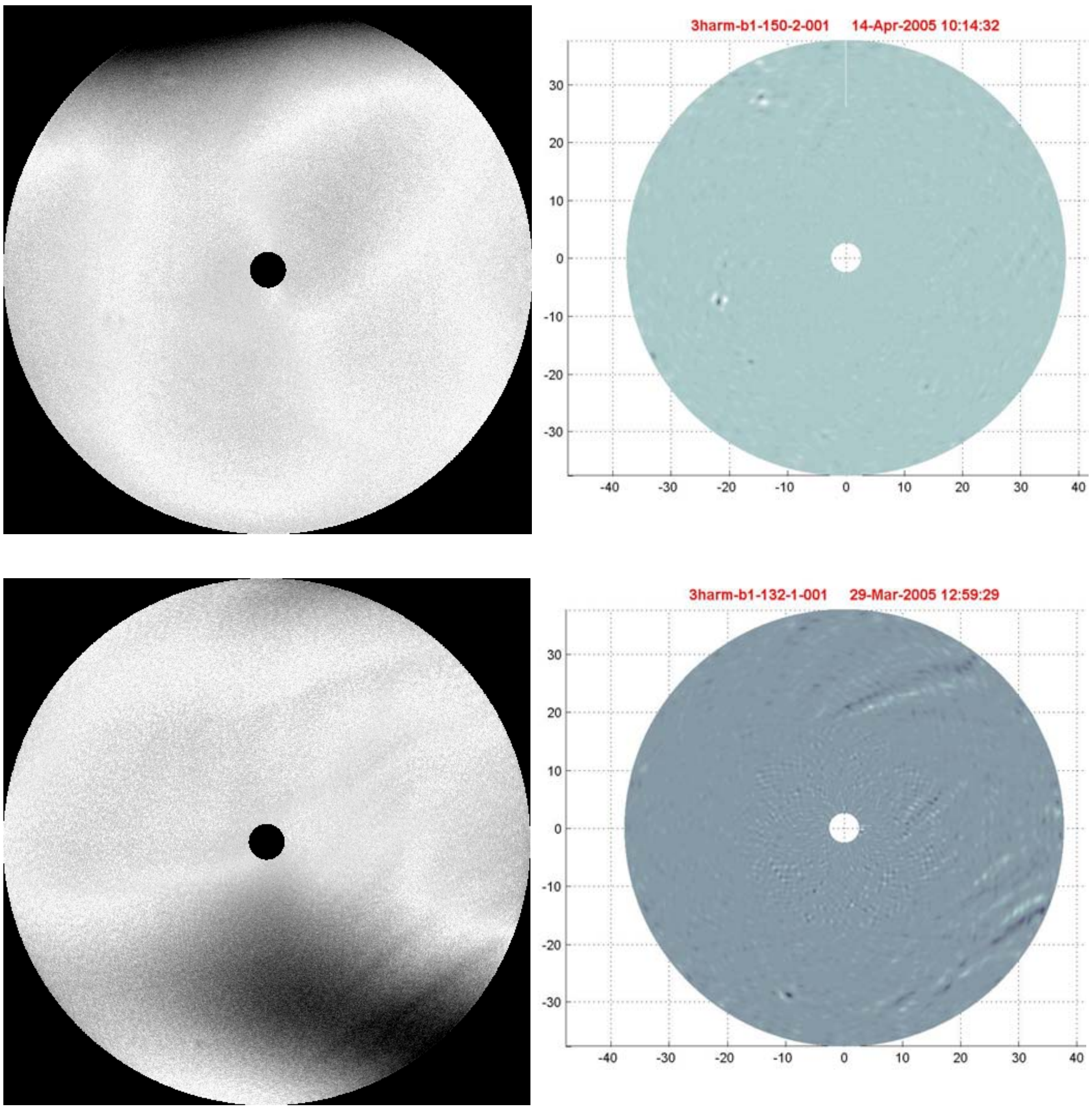

Figure 8 Comparison of scan results before filtering on the left and after filtering on the right

7. CONCLUSIONS

This filter application is a useful tool when the coupling between the signal associated to the long range probe distance (or sample thickness) variation and that associated to inclusions masks the presence of defects. Moreover instead of using indirect criteria (such as appearance on screen), the filter targets precisely the topology variations of interest.

This application is listed in the FermiTools database and is freely available.

8. REFERENCES

[1] W. Singer, D. Proch, A. Brinkmann, "*Diagnostic of Defect in High Purity Niobium*", Proceedings of the RF Superconductivity workshop VIII, Abano Terme, Italy, Oct. 1997

[2] P. Bauer, M. Battistoni, C. Boffo, A. Brinkmann, R. Casperson, D. Connolly, L. Elementi, K. Ewald, O. Lira, F. McConologue, Y. Terechkine, *"Calibration of the SNS Eddy Current Scanner for the Quality Control of the Niobium Blanks for Fermilab's SRF Cavities"*, Fermilab, Technical division, internal note TD-05-016, Feb. 2005

[3] P. Bauer, M. Battistoni, C. Boffo, *"Eddy-Current Scanner Operating Instructions"*, Fermilab, Technical division, internal note TD-04-029, Jun. 2004

APPENDIX A: Software Operating Manual

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QUICK START GUIDE

This document briefly describes the installation process and the main operating features of the *Eddy Current Scanner Data Filter Application* now on named *FIONDA (Filtering Images of Niobium Disks Application)*. For any further information email to FIONDA_support@fnal.gov

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1. INSTALLATION

To install the application download and unzip the package. The following content is available:

1. deploy704.zip ~100 Mbytes
2. ecs.zip ~500 kbytes

The first file contains the MatLab runtime libraries necessary to run the application; the second file contains the application itself. Once the files are downloaded, unzip *deploy704.zip* in a temporary folder and run *MCRInstaller.exe*. This file will launch an installation wizard that simply installs the libraries.
Once the libraries are installed, unzip *ecs.zip* in a convenient place which will become the main folder of the application. There are no path connections with existing applications on the PC which means that this folder can be renamed or moved in a different location at any time.
To start FIONDA click on ***ecs_gui.exe,*** a black window (DOS terminal) appears and, when the necessary libraries are loaded, the FIONDA main window appears as shown in figure 1.

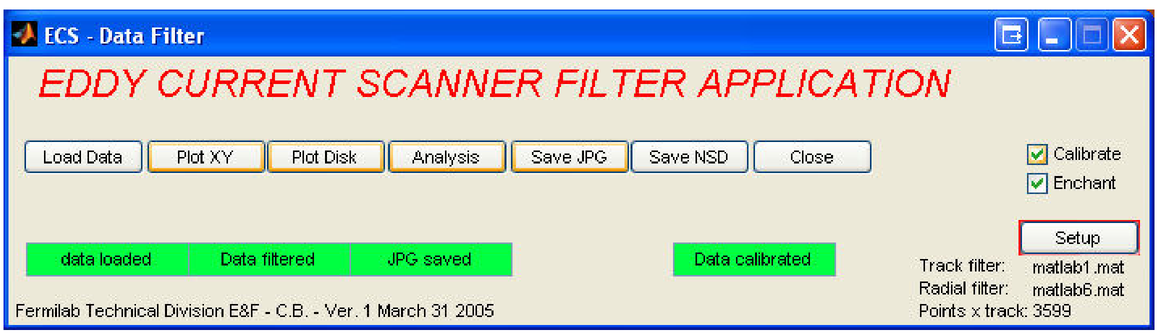

Figure 1 FIONDA Main Window.

2. APPLICATION DESCRIPTION

FIONDA is designed with many options for flexibility, but a simple 2 step process is enough to obtain a filtered picture saved on the hard drive in *jpeg* format keeping the same name as the original *nsd* file.

2.1. ACTION BUTTONS

The data operations are performed through the action buttons shown in figure 2.

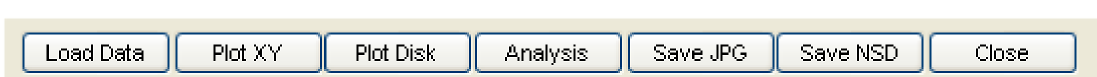

Figure 2 Action Buttons

Each button acts as follow:

Load Data Loads the *nsd* file in the MatLab environment, creates and temporary stores the scanning parameters file, creates and stores the scan data.

Plot XY plots the data in polar coordinates. The result is a rectangular plot where the x axis is the radial direction and the y axis is the circumference. If the filter has been applied, the plot shows filtered data, if the filter has not been applied the plot shows raw data.

Plot Disk plots the data in Cartesian coordinates. The data are mapped on top of the disk surface with the same orientation as Niobscan. If the filter has been applied, the plot shows filtered data, if the filter has not been applied the plot shows raw data. The plot title includes the file name and the date and time.

Analysis applies the filter to the loaded data, plots the results as Plot Disk would do and saves a *jpeg* file with same name as the original *nsd* file.

Save JPG saves the results in a *jpeg* file with same name as the original *nsd* file.

Save NSD saves the data in an *nsd* file that can be opened with Niobscan for additional data analysis. The file name is changed by adding "_f" at its end.

Close closes the application.

2.2. STATUS LEDS

The green status LEDs appear when an operation has been completed, as shown in figure 1. The following LEDs can appear:

Data loaded	when the *nsd* file is uploaded in MatLab
Data filtered	when the filter has been applied
JPG saved	when the picture has been generated and saved on the HD
NSD saved	when the data are saved in *nsd* format
Data calibrated	when the filtered data are calibrated (see options)

2.3. OPTIONS

Since the large and slow height changes are eliminated by the filter, the filtered images show a more complex pattern with respect to the original *nsd* data which can be confusing. In order to consistently compare the different scanned disks, one can use the **calibrate** option. When this option is checked, a single track with a "standard" defect is added at the inner radius of disk. This single line is not visible in the picture but forces the software to use always the same color scale during the visualization. The "standard" defects are chosen from previous scanned and analyzed disks and can be modified (see setup).

When small, the defects are hard to detect in the picture. The **enchant** option allows to plot the square of the signal thus to enchant the hot spots with respect to the background.

2.4. SETUP

The setup button allows changing the filtering parameters. When pressed, the windows shown in figure 3 appears.

Figure 3 Setup window

This window is used to change the source files of the FIR filters. The first column identifies the filter used for the points in a track while the second identifies the filter used along the radial direction. The name of the mat-file containing the FIR polynomial factors must be *matlabXX.mat* where XX is an arbitrary number. In this window one can only change the arbitrary number to match the file name. The filter parameters mat-files must be placed in the root folder of the application. For each of the two filters one must enter the associated delay in the two fields named **Delay 1** and **Delay 2**. Since the calibration is performed adding a line to the data file, one must be sure to apply this feature only if the dimension of the defect line is consistent with the actual data file. In the **Tracks** field one must enter the length in points of the defect line. The defect line is stored in *line.mat* which can be found in the root folder of the application. This file can be changed if necessary. When the data track length does not match the tracks field number stated in this window, the calibration is not performed. The data shown in this window are saved in *filters.ini* which is a text file editable with any text editor. This file contains five tab separated numbers in a single line terminated with a carriage return and a new line with the following meaning:

1. number of the track filter
2. number of the radial filter
3. delay of the track filter
4. delay of the radial filter
5. number of points in a track

In order to update the file from the setup window one must press the **Save File** button. One can also chose to change the parameters in the window without saving the file, in this case, when going back to the main window, one will use the new setup, but when the application is closed and reopened, the old setup will be restored.

The **close** button allows going back to the main window.

The setup parameters are shown also on the main window below the setup button.

3. STANDARD RUN STEP BY STEP

The standard sequence for data filtering is the following:

1. Start **ecs_gui.exe**
2. Check that the setup options appearing below the **setup button** are correct
3. Push the **Load file** button and chose the data file to analyze
4. Wait until the file is loaded (check the wait bar appearing as in fig. 4)
5. A sound plays when the file is loaded and the green LED shows up
6. Check the suitable options (enchant and/or calibrate)
7. Push the **Analyze** button to start the filter
8. Wait until the data are analyzed (check the wait bar appearing as in fig. 4)
9. A sound plays when the process is over
10. A picture of the filtered data appears and the jpeg file is saved
11. Green LEDs show up according to the options chosen
12. Close the picture and restart the process from step 3

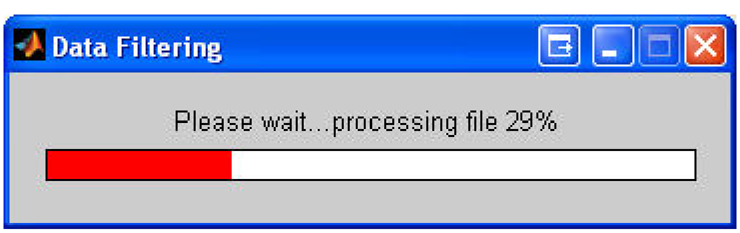

Figure 4 Wait bar

4. WARNINGS

The following warnings and alarms have been implemented:

- When the data file has not been loaded yet: a warning window shows up if any action button other than **load file** is pushed
- When the **close** button in the main window is pushed: a warning window shows up to confirm the action
- When the **close** button is pushed in the setup window after changing some parameters: a warning windows shows up to confirm the action
- When the length of the defect line is different with respect to the data set and one checks the **calibrate** option: a warning shows up stating that the calibration was not performed

5. REFERENCES

[1] P. Bauer, C. Boffo, L. Elementi, K. Ewald, "Eddy Current Scanner Operating Instructions", Fermilab, Technical Division, internal note TD-04-029, Aug. 2004

[2] P. Bauer, C. Boffo, "FIONDA (Filtering Images Of Niobium Disks Application) Filter application for Eddy Current Scanner Data analysis", Fermilab, Technical Division, internal note TM-2313-TD May 2005

[3] M. Battistoni, P. Bauer, C. Boffo, A. Brinkmann, R. Casperson, D. Connolly, L. Elementi, K. Ewald, O. Lira, F. McConologue, R. Nehring, Y. Terechkine, "Calibration of the SNS Eddy Current Scanner for the Quality Control of the Niobium Blanks for Fermilab's SRF Cavities", Fermilab, Technical Division, internal note TD-05-016, Feb. 2005