UNIVERSITÀ DI PISA

Fermilab

Dipartimento di Ingegneria dell'Informazione

corso di laurea magistrale in Ingegneria Robotica e dell'Automazione

Calibration Magnet XY Stage System

Readout Automation and Field Maps

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Abstract

To calibrate the Hall Probes for mu2e experiment, a Calibration Magnet is needed.
In this Magnet, the Uniform and Constant Region is needed to be identified.
A LabVIEW Hardware Front-End and a MATLAB software have been designed to:

1. Implement an Automatic DAQ System from the PT2026 NMR Probe
2. Store, Analyse and Plot the Acquired Data
3. Identify the Calibration Region

Contents

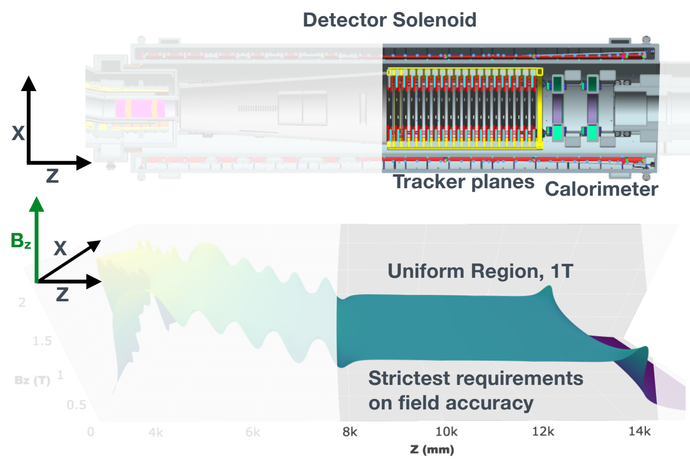

Figure 1: Simulation of the magnetic field inside Detector Solenoid

1 Problem Statement

1.1 mu2e Technical Requirements

In order to obtain relevant results, **strict requirements in terms of uniformity and accuracy** are needed by the Detector Solenoid of the mu2e experiment (Fig. 1).
To respect the requirements five Hall Probes are needed.
To calibrate these probes a **Calibration Magnet** is used.

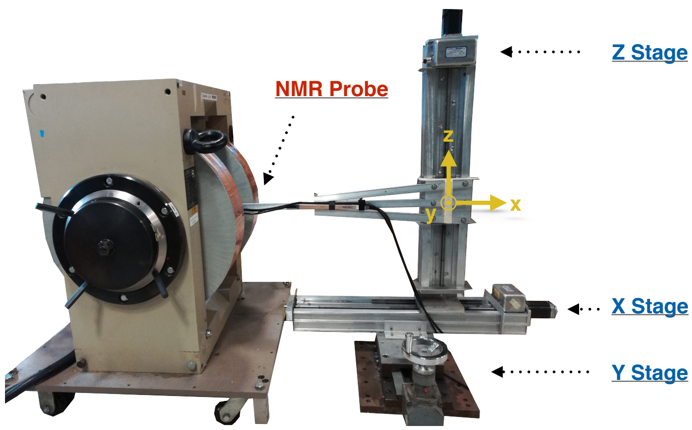

Figure 2: Experimental set-up for magnet mapping

1.2 Calibration Magnet's Plant

In the Calibration Magnet, there is a Uniform and Constant Field Region that needs to be identified: **The Calibration Region**.
To do that a dedicated plant has been built. In particular this plant is composed by:

- **A Cooling Plant**, to guarantee a stable temperature for the magnet's coils
- **A Data Acquisition** (DAQ) System, to acquire the data from the magnet.

For this project just a part of the DAQ System has been used (Fig. 2):

- The GMW 3474-140/280 250mm **Calibration Magnet**
- The Metrolab PT2026 **NMR Probe**
- A 750mm Two Axis Actuated Stage (XZ), controlled by NI Motion
- A 750mm One Axis Manual Stage (Y)

Note: The Axis have opposite directions respect to the direction of motion.

1.3 Manual Acquisition

To acquire a single point from the remote interface (NI Measurement and Automation Software) the user used to:

- Select the desired surface with the Y Stage
- Move the motors in the desired point
- Acquire the signal from the PT2026 Software
- Store the data in an excel spreadsheet

This approach is not suggested for a Calibration Process due to the **introduction of human errors** that affects the precision of the process in an unbounded way.

Moreover the above procedure is tedious and is a inefficient use of human effort in terms of time and money.

1.4 Main Goal

Two are the goals of this project:

1. **Automate the Acquisition** of the magnetic field
2. **Automate the Analysis** of the Data, returning a colour-coded plots of the Magnetic field.

In order to do that, some design goals have been chosen:

- A simple and lightweight program should be designed, to reach as soon as possible significant results
- A configurable and flexible interface should designed, to make the process parameters-independent and precise (in terms of repeatability of the experiment)

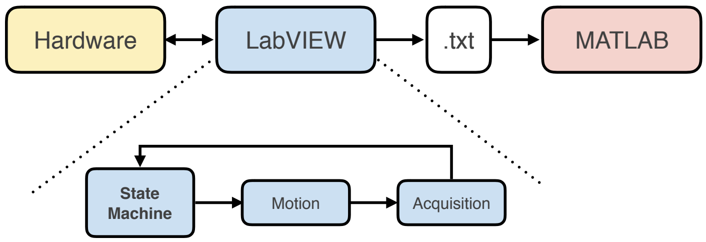

Figure 3: Block diagram of the Software

2 Software Design

2.1 Block Diagram

In Fig. 3 the Software Block Diagram is shown. It is composed by:

- a **Front-End LabVIEW Application** that moves the motors, acquires the signal in a given surface and store the data in a `".txt"` file
- a **MATLAB Script** that reads and analyses the data from the `".txt"` file

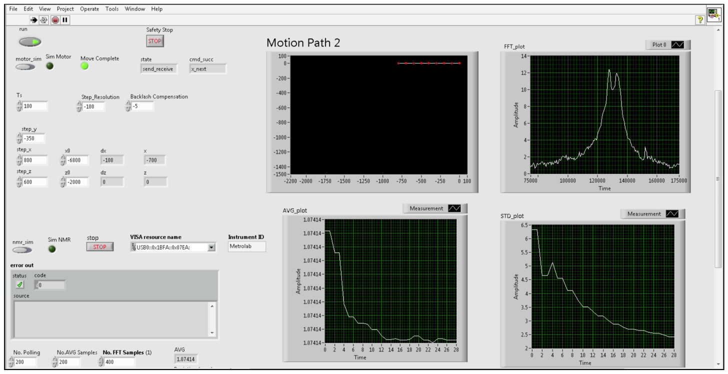

Figure 4: LabVIEW software interface

2.2 LabVIEW Interface

The LabVIEW Software interface is shown in Fig. 4. It is composed by:

- A panel to insert **coordinate of the y stage** and the **mapping grid** information
- A panel to select the desired number of samples
- Plots to monitor the goodness of the mapping

The structure of the program is straightforward:

- The **initialisation** process put the motors from the origin frame to **desired initial position**
- Once reached the origin,a **State Machine** gives commands to the motors, in order to do a **line by line scan** as it is shown in Fig. 5
- When the motors have finished the movement, the **Probe searches if a measurement is possible**. If it is, then it returns the desired amount of samples and rises a ready flag for the state machine.
- After the measurement, the samples are stored in a `".txt"` file and the next command is given by the state machine.
- When all the points of the grid have been scanned, the state machine makes the motors to **goes back to the origin frame**.

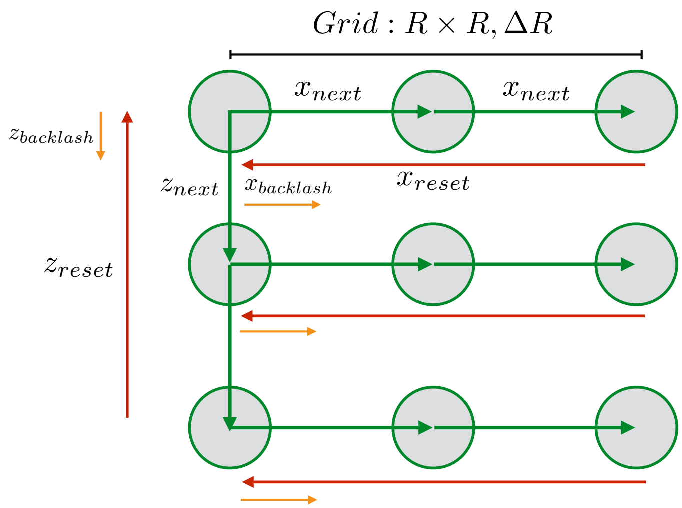

Figure 5: Raster Scan commands of the State Machine

2.3 MATLAB Interface

The MATLAB Software interface is shown in Fig. 6.
It is composed by **4 folders** and **7 files**.

Files:

1. `main2d.m`: takes a `".txt"` **file as input** and executes the Import, Analysis, Plotting and Export Script for the **input file**

2. `main3d.m`: takes a **folder of** `".txt"` **files as input** and executes the Import, Analysis, Plotting and Export Script **for all the files in the folder**

3. `Data_Import.m`: scans an input .txt file and stores the data in a MATLAB data structure

4. `Data_Analysis.m`: takes the output data of Data_Import, extracts the Mean from Field Amplitude samples, the Peak from the NMR FFT Input signals, assigns a colour based on the extracted information and creates a data structure that contains all the extracted information from the signals.

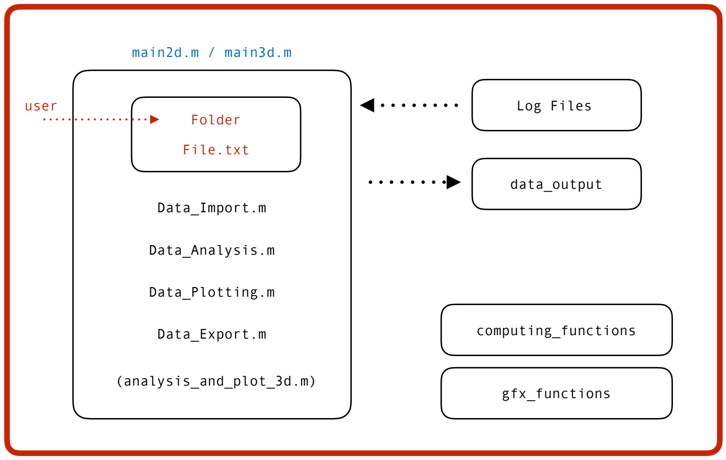

Figure 6: MATLAB Software Block Diagram

5. `Data_Plotting.m`: returns the 1D,2D and 3D Plot of the output data of Data_Analysis.m

6. `Data_Export.m`: Add graphics elements to the plots and export dataset and figures (in .fig and .pdf extensions)

7. `analysis_and_plot_3d.m`: create a **unique data structure** from all the files imported by main3d.m and plot the 3d maps of the Magnetic Field

Folder:

1. `Log Files`: contains the .txt output files from LabVIEW

2. `data_output`: contains the exported files from `Data_Export.m`

3. `computing_functions`: contains numerical functions used in the scripts

4. `gfx_functions`: contains functions used to plot graphics elements

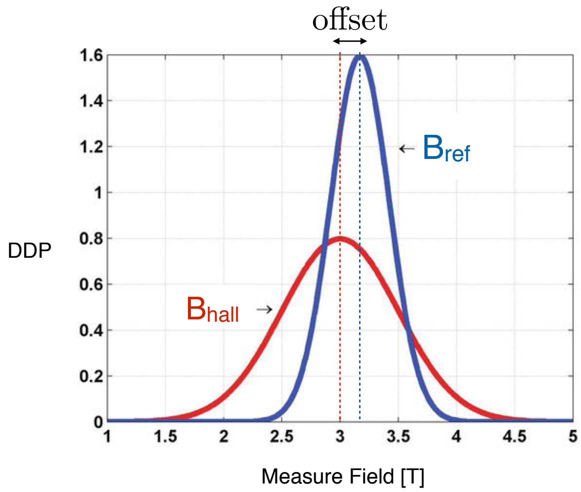

Figure 7: Calibration Process of a Gaussian scalar measurement

3 Calibration Process

3.1 How to Calibrate a Vectorial Measure

In order to calibrate an Hall Probe Sensor, the following information are needed for each point of the space :

1. An **accurate (scalar) reference value**, to regulate the offset to zero and to adjust the scale factor to a proper value (Fig. 7)

2. An **estimation of the uniformity** of the field, to verify the consistency of the calibration.

Those information are acquired with the **PT2026 NMR Probe**.

3.2 NMR Probe Data Acquisition

3.2.1 NMR Probe Working Principle

To correctly interpret the measured data, the NMR working principle should be explained.

- "A nucleus with spin 1/2 will have **2 possible orientations**.
  In the **absence of an external magnetic field**, these orientations are of **equal energy**.
  If a **magnetic field is applied**, then the **energy levels split**." [1]

- "Spin states which are **oriented parallel** to the external field are **lower in energy** than in the absence of an external field.
  In contrast, spin states whose orientations **oppose the external field** are **higher in energy** than in the absence of an external field."[1]

- "The **rotational axis of the spinning nucleus** cannot be orientated exactly parallel (or anti-parallel) with the direction of the applied field B_0 but must **precess about this field** at an angle, with an angular velocity given by the expression: $\omega_0 = gB_0$
  Where ω_0 is the precession rate called the **Larmor frequency**.
  The constant g is called the magnetogyric ratio." [1]

- "This **precession process generates an electric field** with frequency ω_0.
  If we irradiate the sample with radio waves (MHz) the proton can absorb the energy and be **promoted to** the less favorable **higher energy state**.
  This absorption is called resonance because the frequency of the applied radiation and the precession coincide or resonate."[1]

- "While frequency is not a measure of energy, the simple relationship $E = h\nu$ makes this substitution understandable. "[1]

- "A single oscillator (transmitter) is used to generate a pulse of **electromagnetic radiation of frequency** ω."[1]

- "**When the pulse ends**, the nuclei relax and return to their equilibrium positions, and the signal decays.
  This decaying signal contains the **sum of the frequencies from all the target nuclei**. [..] It is mixed with a lower frequency signal to produce an interferogram of low frequency. This interferogram is digitized, and is called the **Free Induction Decay, (FID)**.
  Fourier transformation of the FID yields a **frequency domain spectrum**." [1]

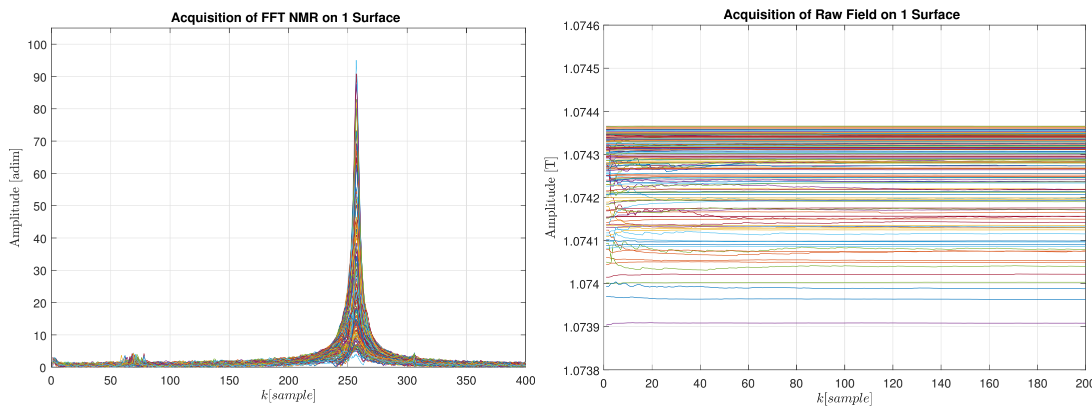

Figure 8: Raw Data of a surface of the Magnet, measured by PT2026 NMR Probe

3.2.2 NMR Raw Data

The PT2026 NMR Probe that have been chosen for the project's objective are:

1. **The Fourier Transformation of the FID**
2. **The Amplitude of the Magnetic Field**

A complete acquisition of one surface of the Magnet is shown in Fig. 8
The former gives a **Uniformity Information**:
Let's suppose that there are **n nuclei** in the probe and there are **m different directions of field lines**.
Then the FFT of the FID (if m is small enough to allow the measurement) will return **m** small different peaks.
On the other hand, **if the field is uniform** the FFT is composed by **one clear peak**.

The latter use the Bandwidth of the FFT to **estimate the Larmor frequency** ω_0 and **compute the Magnetic Field** (using $\omega_0 = \mathbf{gB_0}$)

In both cases what is needed to be decided is:

1. The Number of **Acquired Samples**

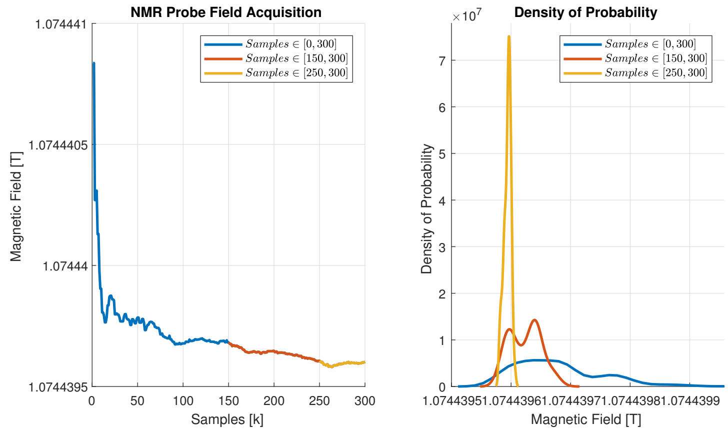

Figure 9: Analysis of the stabilisation of the Amplitude Signal

2. **A Quality Factor**: a scalar value that evaluate the goodness of each signal

3.2.3 Time Signal of Field Amplitude

In Fig. 9 an acquisition of the Magnetic Field Amplitude is shown:
On the **left** plot, a **time domain plot** is presented. In this acquisition the probe is stabilizing the signal.
On the **right** plot there is the **Estimated Density of Probability for different cropped sequences**. It is shown that if all the samples are taken into account, the average value is corrupted due to the overshoot. On the other hand, if we want to arrive at a Gaussian like event with a good accuracy, **at least 250 samples are needed**.

The best solution should have been to acquire 1000 samples and to do a stochastic analysis on the last 750 samples, but it would have required too much time to map the magnet.
In this project a **reasonable trade off** was thought to be an acquisition of **250-300 samples** and use the **average on the last 50 values** as quality factor.

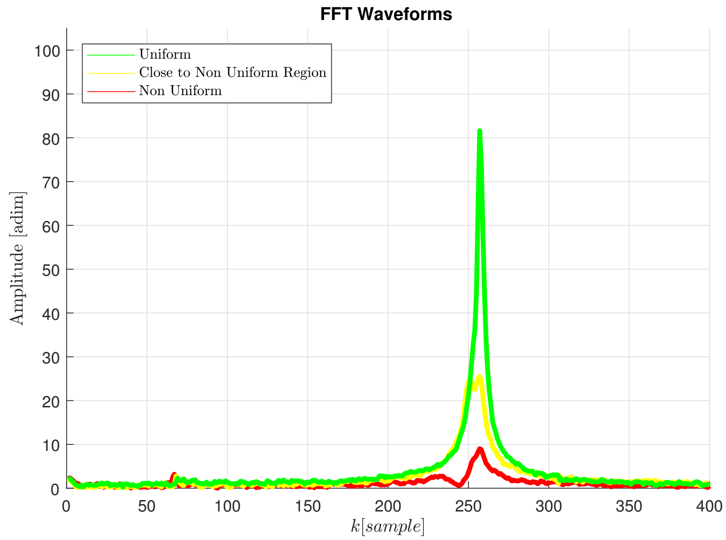

Figure 10: FFT Waveforms

3.2.4 FFT of FID signal

In Fig. 10 the possible waveforms of the FFT of FID signal are shown:

- **400 samples** are enough to cover all the bandwidth of the signal
- The **Uniformity** information is **encoded in the shape of the signal**
- A good estimation of the Uniformity is the **peak value of the waveform**

3.2.5 Data Visualisation

Thresholds are set using the **Average value of the cropped samples** for the Magnetic Field Amplitude and the **Peak Value** for the FFT of FID signal.
In Fig. 11 an Analysed Dataset is shown.

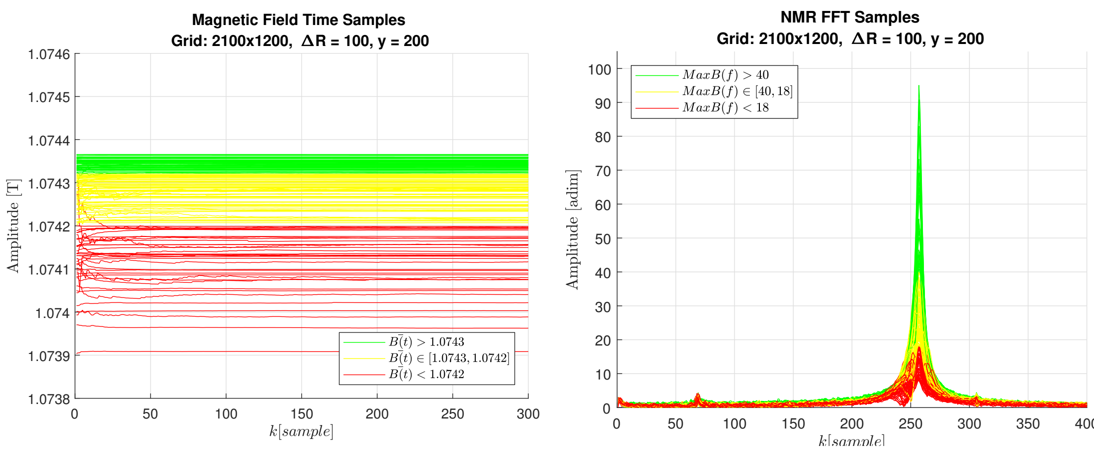

Figure 11: Example of data visualisation after the Software Analysis

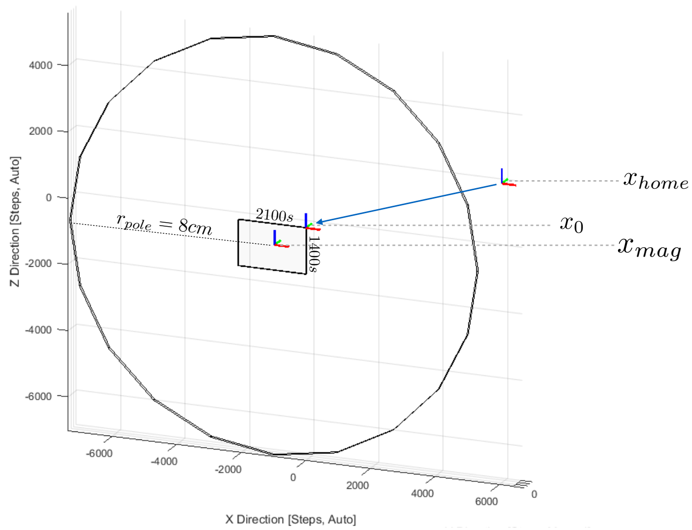

Figure 12: Example of Searching Area

4 Data Analysis

4.1 Searching Area

In this section the analysed data is shown.
Data are sampled in a **small region in the neighbourhood of the pole's center**.
An example of an acquisition is shown in Fig.

- x_{home} is the rest position of the probe
- x_0 is the position of the first acquired sample
- x_{mag} is the estimated position of the magnet

Note 1: The units of measure used in the following plots are in steps or in mm.
The conversion factor is shown in Table 4.1

Note 2: The X and Z position are measured in relative steps respect the end of the screw;
The Y position is measured in relative steps respect the 'first available 0 position on the positive direction of Y axis' of the manual stage.

	X	Y	Z
Scale Factor [$\frac{\mu m}{step}$]	12.7	25.4	12.6

Table 1: Conversion Table: from steps to μm

4.2 4 Slices, ΔR = 100 steps

This Acquisition have the following settings:

- 4 slices: 0, 100, 200, 300 steps
- $\Delta R = 100$ steps
- Grid = 2100 x 1200 steps
- x_0 = (-5500,-1550) steps
- $I = 200A$
- Number of Samples (AVG) = 300 Samples
- Waited Stabilisation Tim: 2 days
- Mapping Time: 1.30 hours

4.2.1 Amplitude Analysis

In Fig. 13 it is shown the Acquisition of the Field Amplitude for each surface: **The Magnetic Field increases in the neighbourhood of the poles and diminishes in the centre**. The expected field form the theory of electromagnetism is consistent with this result.

In Fig. 14 it is shown the space distribution of average value of magnetic field. This plot has the following interpretation:

- Coordinates of a given searching area are on 2 axis
- Average value of magnetic field related to each (x, y) coordinate is the value of z coordinate.

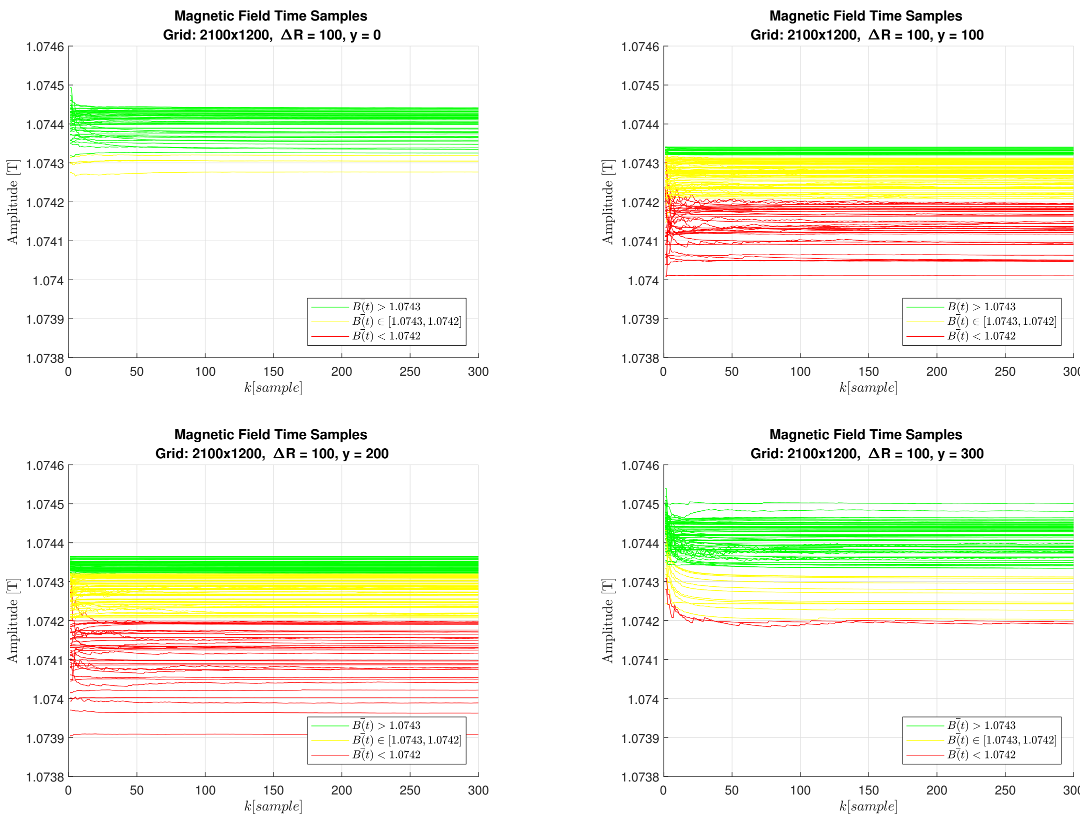

Figure 13: Field amplitude samples for each surface

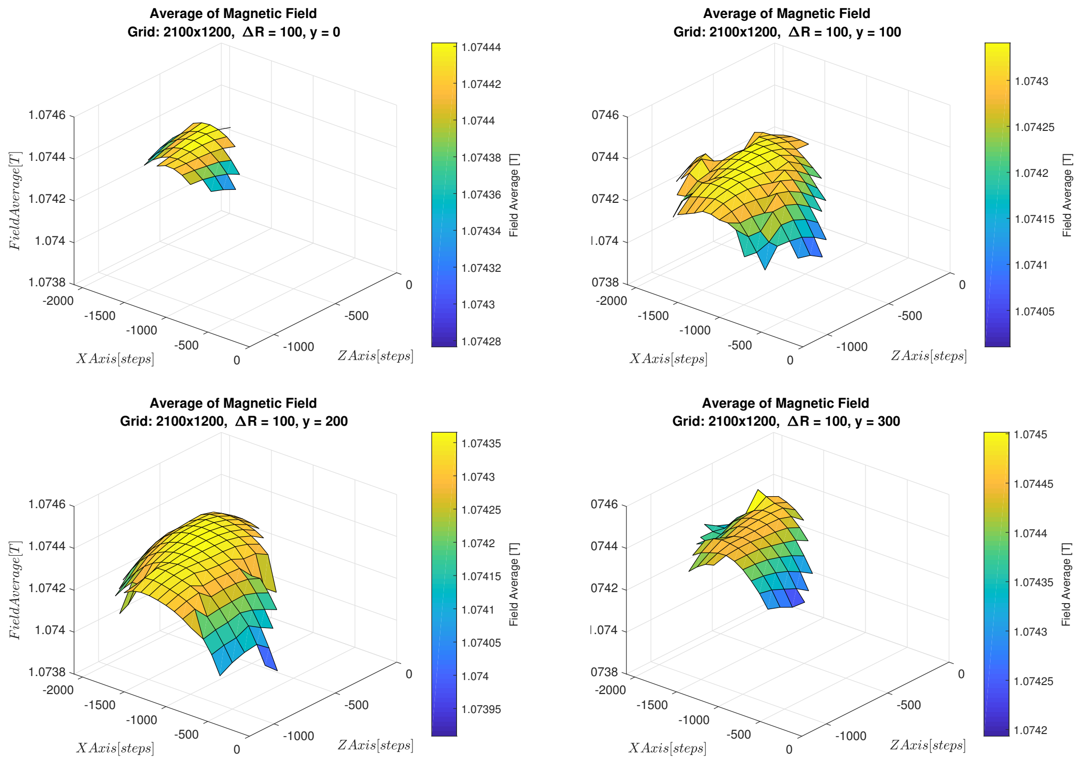

Figure 14: Space distribution of average value of magnetic field

Due to that, **the more a plot is flat, the more a surface has a constant magnetic field**. And in this case the flattest plot is the one with $y = 200$.

In Fig. 14 the space distribution is seen from above. It shows the number of points that have been measured. In fact if the measurement is bad or the field is not enough uniform to allow a correct measurement, its value is not considered in the plot.

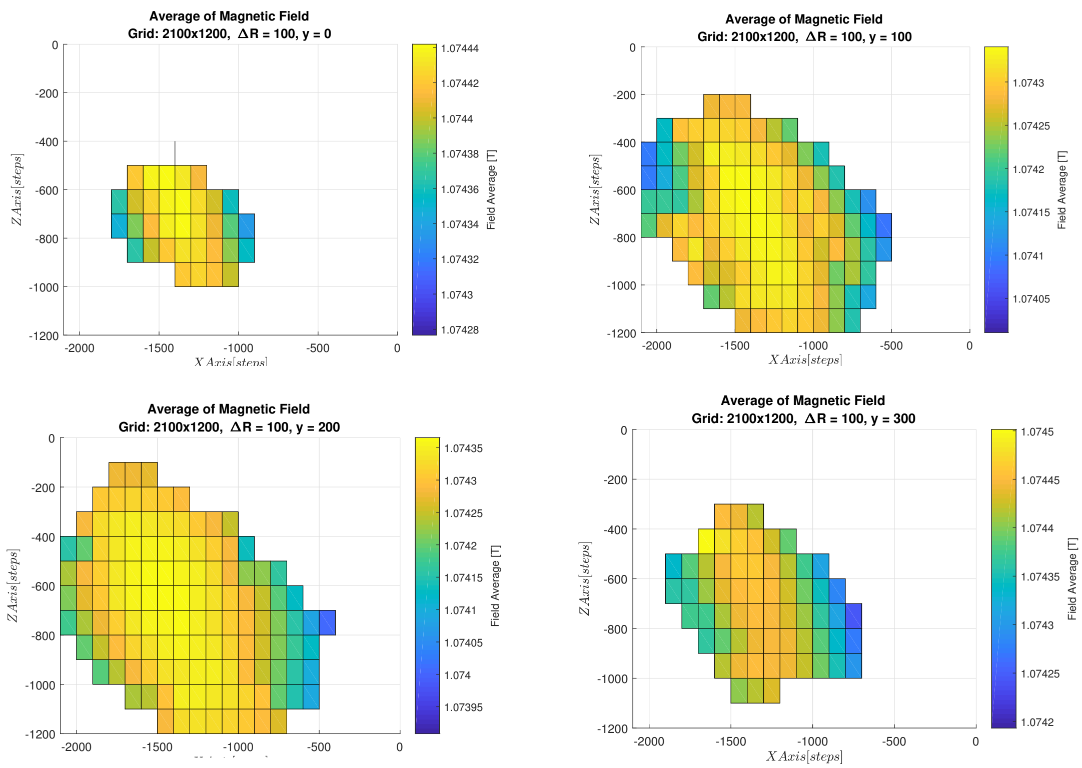

Figure 15: Space distribution of average value of magnetic field (view from above)

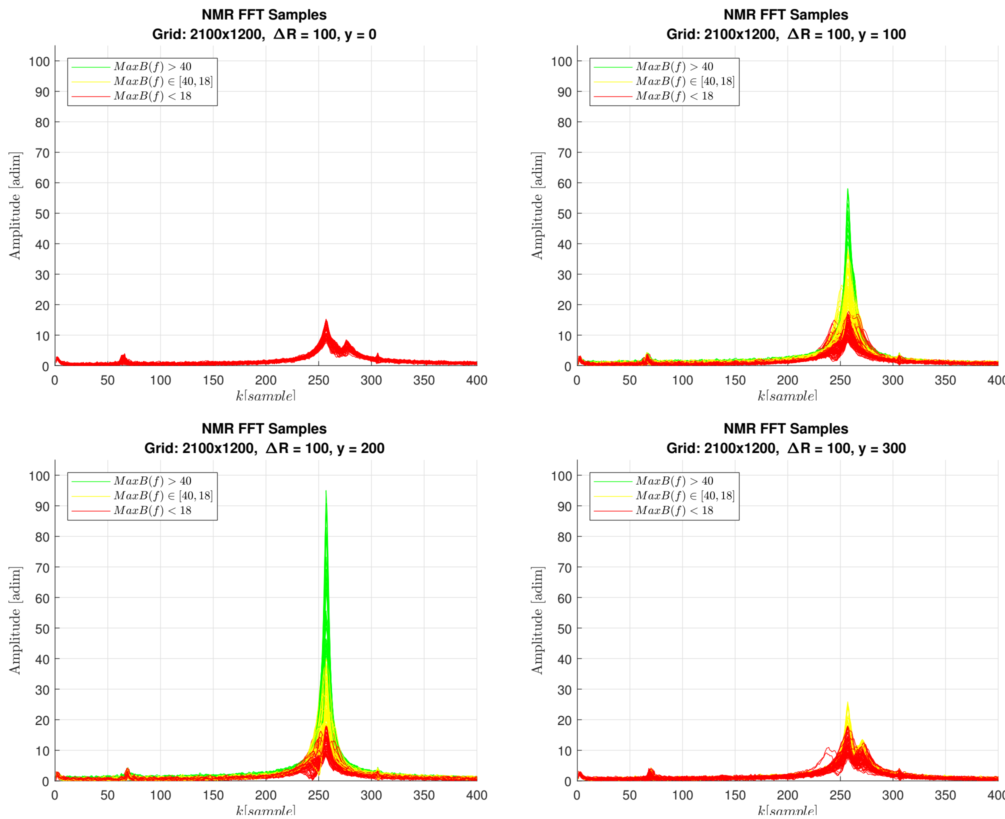

Figure 16: FFT of FID signal for each surface

4.2.2 Peak Analysis

In Fig. 16 it is shown the FFT of FID Signal for each surface.
The Green signals represent the uniform measurements: It is shown that the field is **not uniform in the neighbourhood of the poles but it is uniform in the centre of the magnet**. In particular the biggest peak value is in the slice with $y = 200$;

In Fig. 17 it is shown the Space distribution of FFT Peak values. This plot has the following interpretation:

- Coordinates of a given searching area are on 2 axis.
- FFT Peak Values related to each (x, y) coordinate is the value of z coordinate.

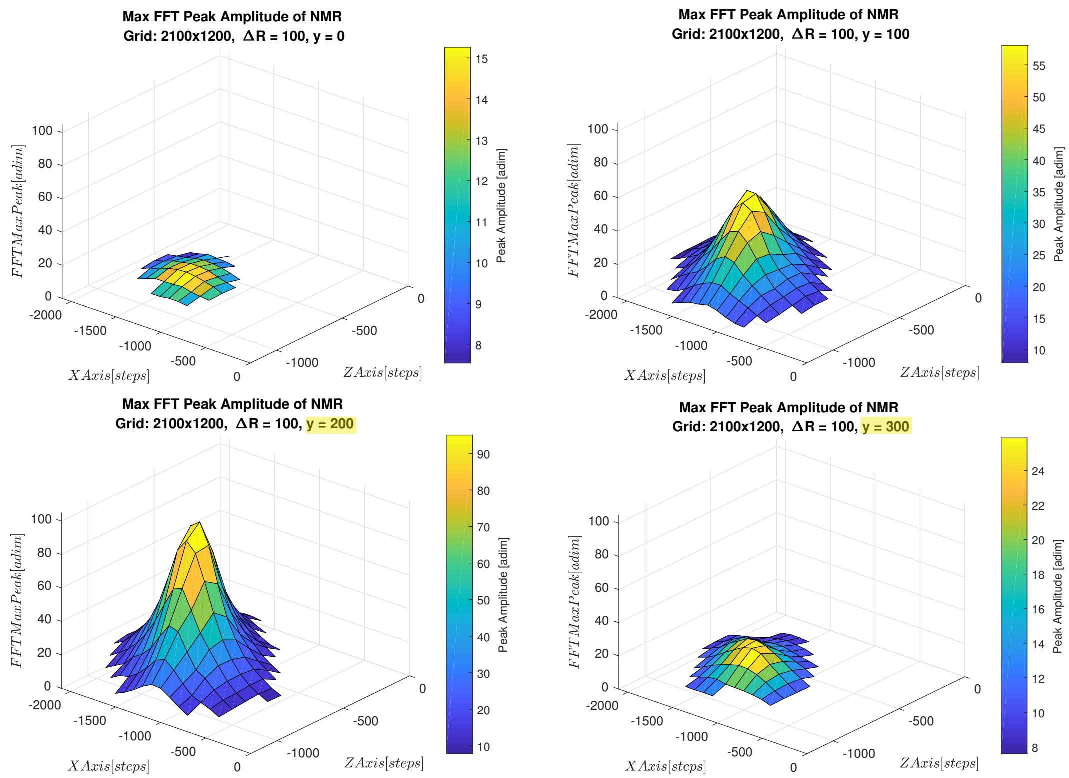

Figure 17: Space distribution of FFT peak values

Due to that, **the more a plot is flat, the more a surface has non-uniform magnetic field**. And in this case the flattest figures are the ones close to the poles ($y = 300$, $y = 0$).
On the other hand, the two bell-shaped plots ($y = 100$, $y = 200$) are the most uniform ones.

The same information can be extracted from the view from above of this plot, in Fig. 18

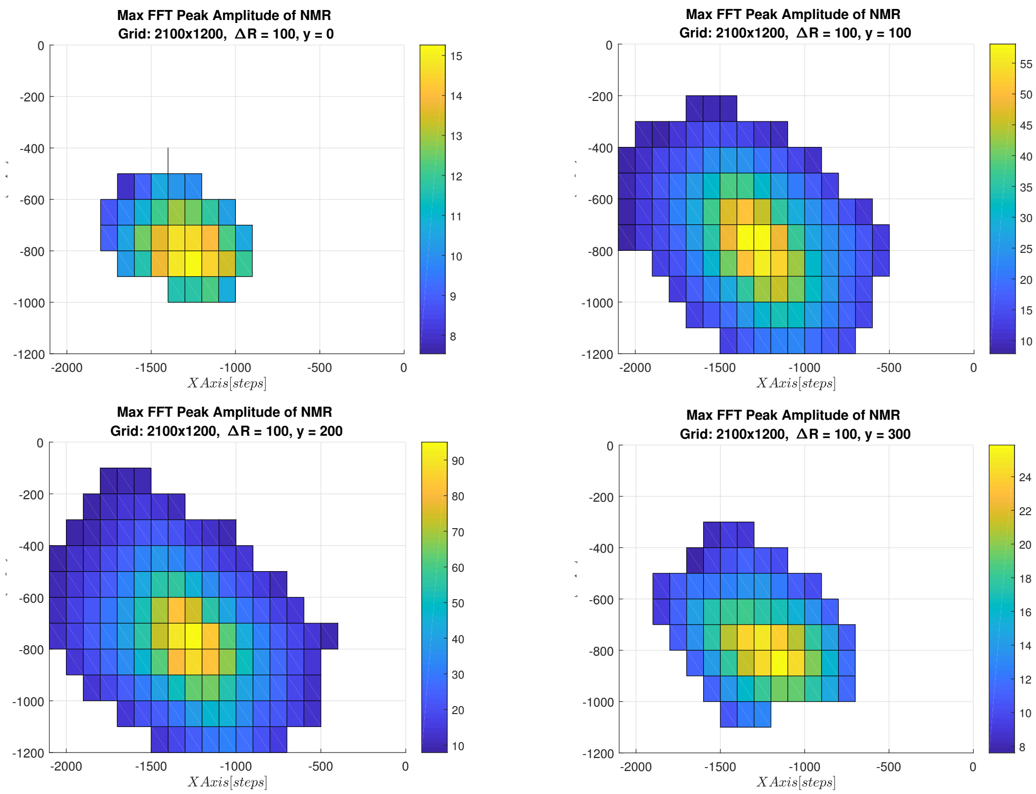

Figure 18: Space distribution of FFT peak values (view from above)

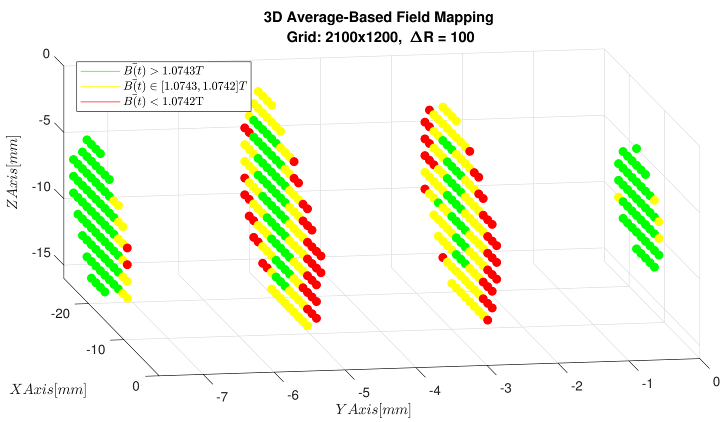

Figure 19: Field Map based on average value of the field

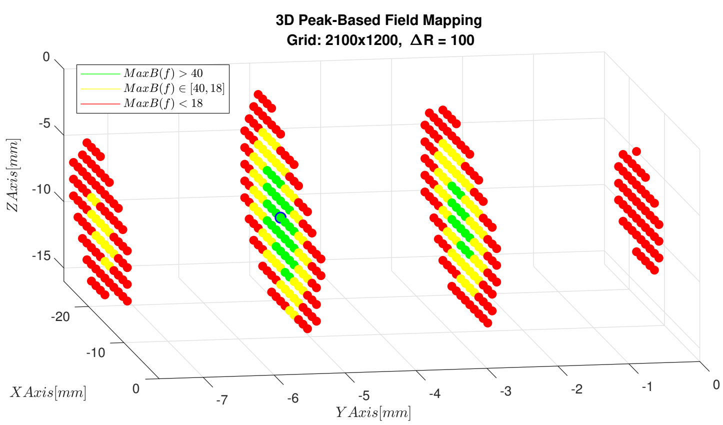

Figure 20: Field Map based on uniformity of the field

4.2.3 3D Maps

A 3D map of the Magnetic Field is shown in Fig.19 The thresholds that defines the colour code are based on the average value of each point. As shown in the previous plots, the field is more intense in the neighbourhood of the poles.

On the other hand, Fig.20 shows a 3D map with thresholds based on the peak value related to each point. As shown in the previous plots, the field is more uniform in the central slices.
In particular the uniform region is included in the slices located from 2 to 6 mm from the 0 of the Y axis.

To validate results a second mapping has been done, with doubled resolution.

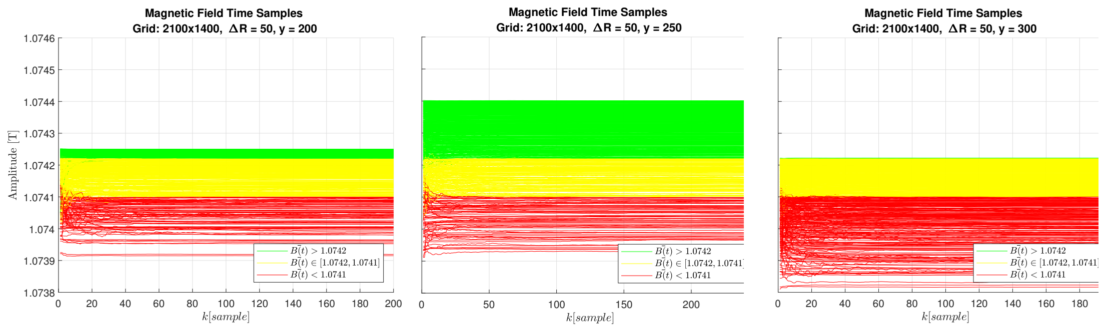

Figure 21: Field amplitude samples for each surface

4.3 3 Slices, $\Delta R = 50$ steps

This Acquisition have the following settings:

- 3 slices: 200, 250, 300 steps
- $\Delta R = 50$ steps
- Grid = 2100 x 1400 steps
- x_0 = (-6200,-1600) steps
- $I = 200A$
- Number of Samples (AVG) = 250/200 Samples
- Waited Stabilisation Tim: 1/2 days
- Mapping Time: 6 hours

4.3.1 Amplitude Analysis

In Fig.21 it is shown the Acquisition of the Field Amplitude for each surface. This acquisition has not consistent results respect the one with $\Delta R = 100$:

- **The amplitude value is decreased of** $10^{-4}\ T$
- **The maximum of the magnetic field is at** $y = 250$

In Fig. 22 it is shown the Space distribution of average value of magnetic field. Also this plot shows some weird results:

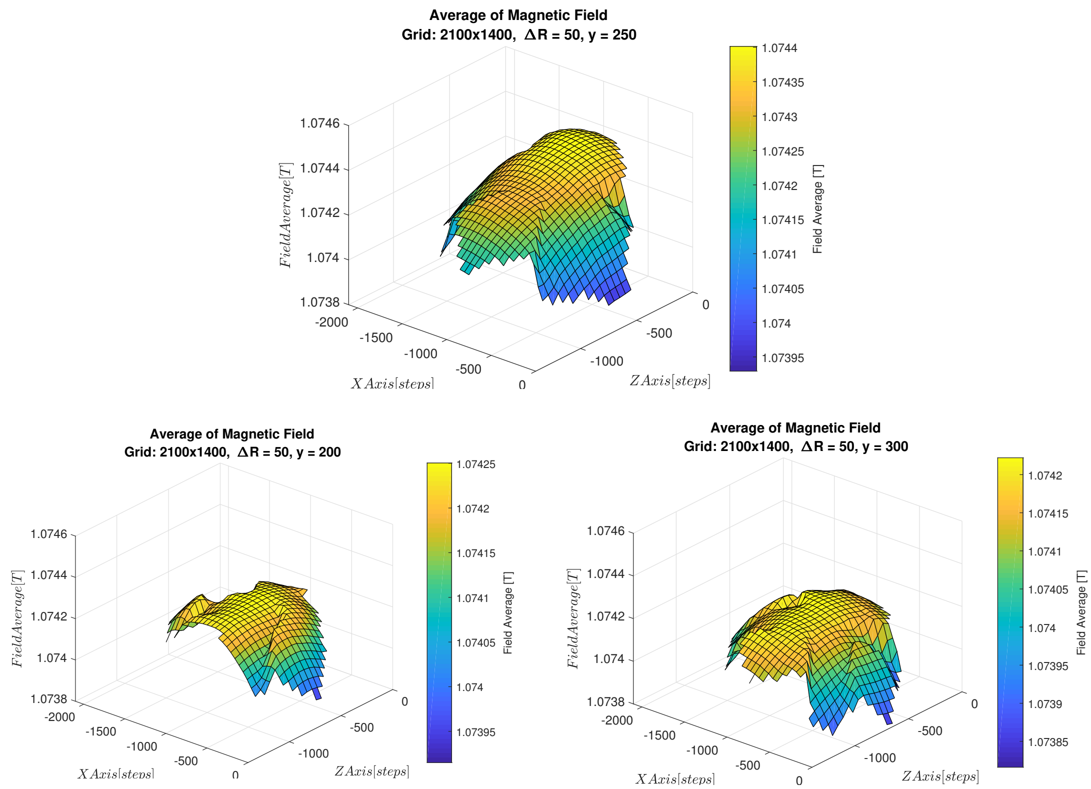

Figure 22: Space distribution of average value of magnetic field

- the $y = 250$ surface **was expected to be constant: instead, it has a positive linear slope on the Z axis**;
- $y = 200$ and $y = 300$ are more flat than $y = 250$;

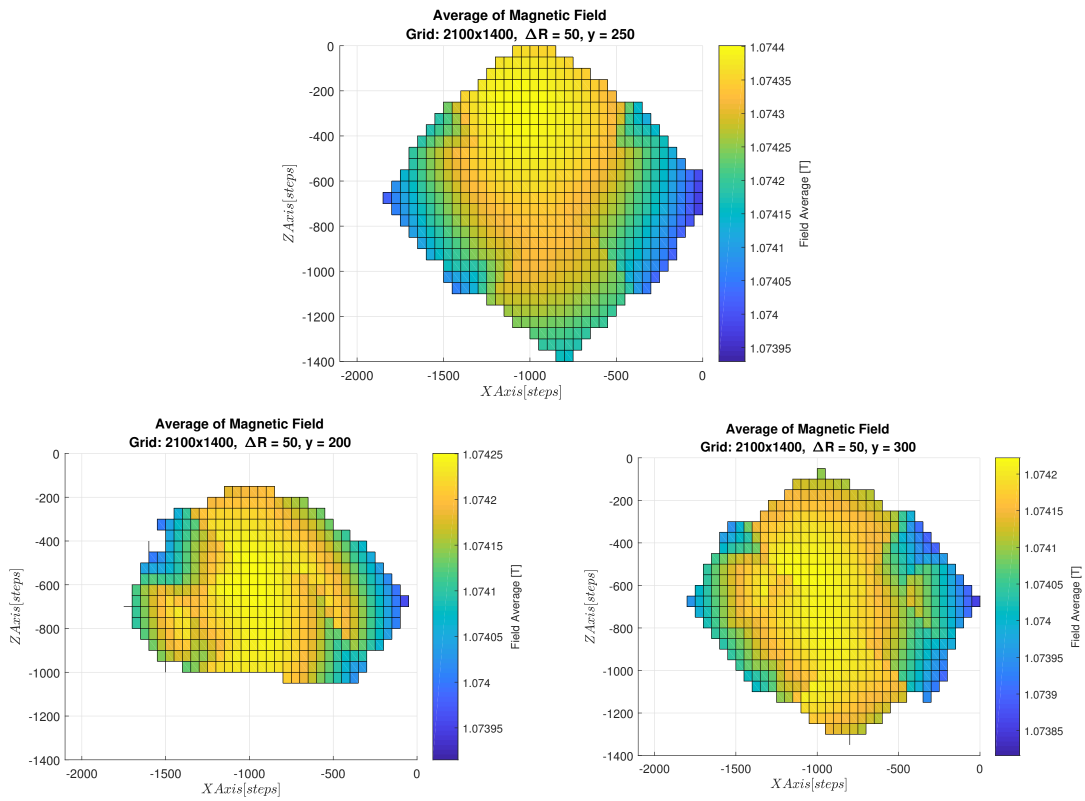

Figure 23: Space distribution of average value of magnetic field (view from above)

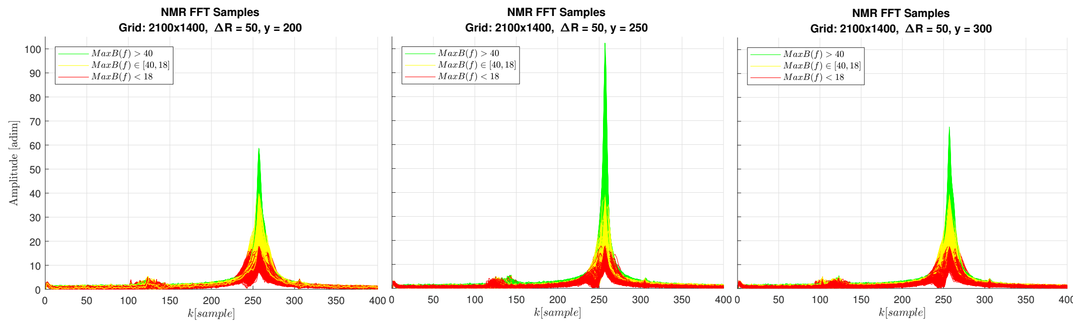

Figure 24: FFT of FID Signal for each surface

4.3.2 Peak Analysis

Same results could be extracted from Fig. 25.

In Fig.24 is shown the FFT of FID Signal for each surface.
All the slices present a clear green area. In particular the biggest peak value is in the slice with $y = 250$;

The same information can be extracted from Spacial Distribution in Fig.25 and Fig.26 .

Although the average values are not reliable, the **Uniformity Analysis confirm that not all the collected data are corrupted**.
Then the **Average Analysis results could be justified by an unsteady thermalisation of the magnet.**

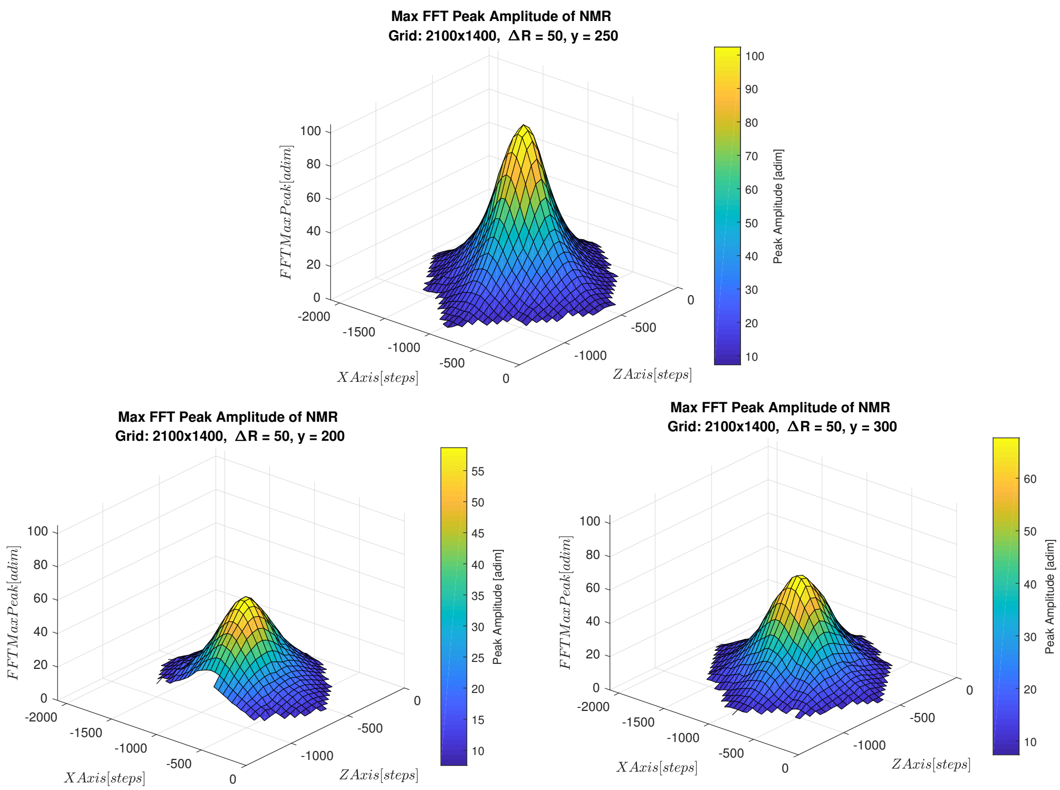

Figure 25: Space distribution of FFT peak values

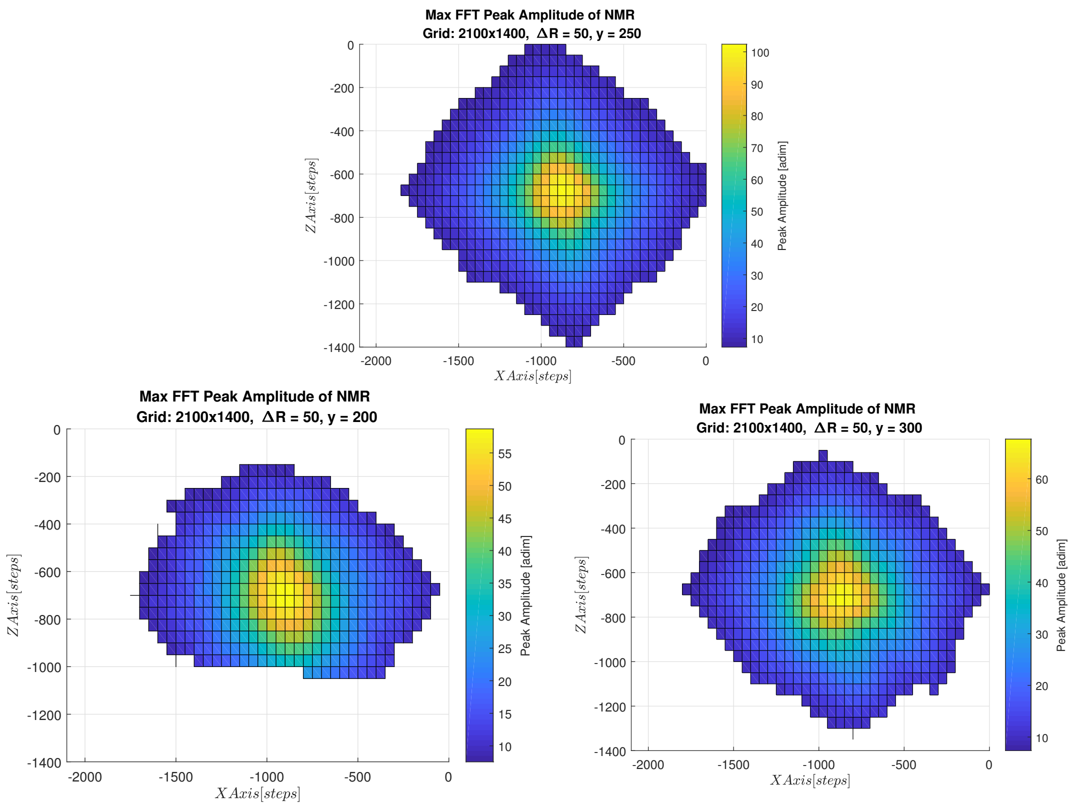

Figure 26: Space distribution of FFT peak values (view from above)

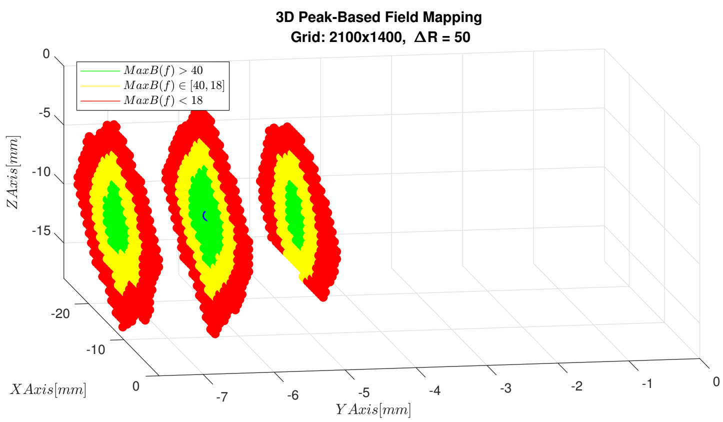

Figure 27: Field Map based on average value of the field

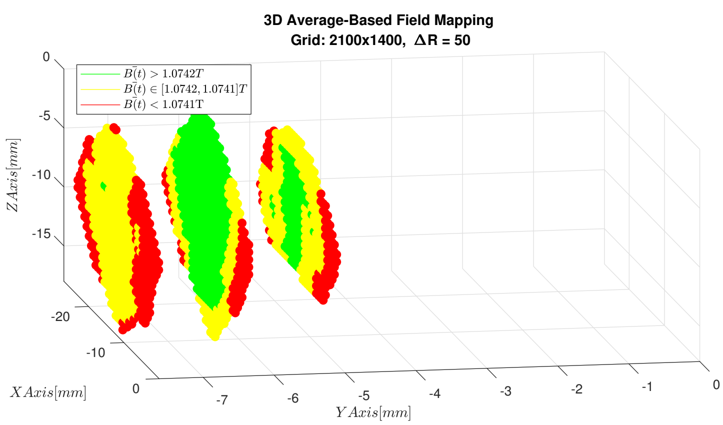

Figure 28: Field Map based on uniformity of the field

4.3.3 3D Maps

A 3D map of the Magnetic Field is shown in Fig. 19 The thresholds that defines the colour code are based on the Average value of each point.
This plots confirm that the average values of this map are corrupted, at least for the central slice ($y = 250$).

On the other hand, the Peak-based 3d Map (Fig. 20) shows that all the mapped slices are inside the uniform region.

A more complete map of the magnet was not possible to be acquired due to time constraints (Magnet Division has to change the cooling plant) ; Nevertheless, one more acquisition with increased resolution has been done to show the performance of the developed software.

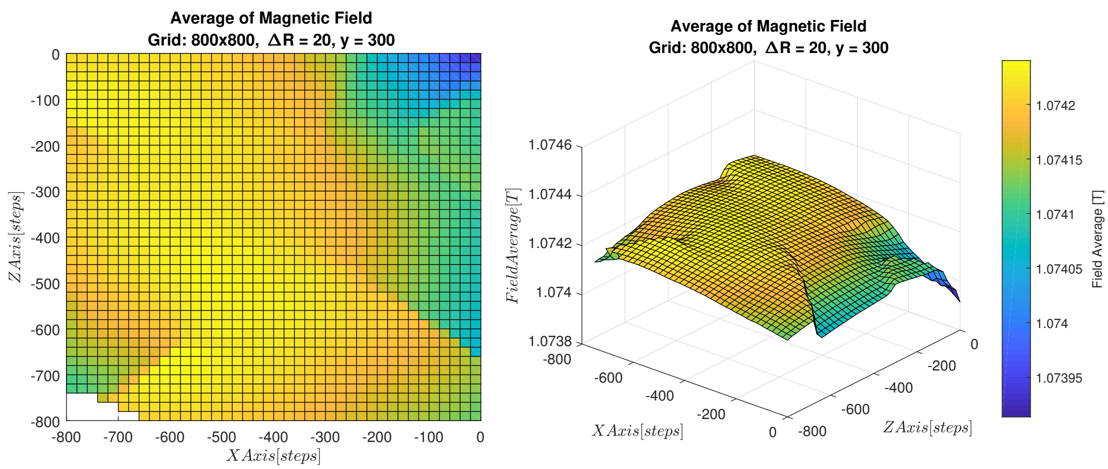

Figure 29: Space distribution of FFT peak values

4.4 1 Slices, ΔR = 20 steps

This Acquisition have the following settings:

- 1 slice: 300 steps
- $\Delta R = 20$ steps
- Grid = 800 x 800 steps
- x_0 = (-6200,-2000) steps
- $I = 200A$
- Number of Samples (AVG) = 300 Samples
- Waited Stabilisation Tim: 1 day
- Mapping Time: 8 hours

4.4.1 Amplitude Analysis

In Fig. 29 it is shown the Space distribution of average value of magnetic field.
It is the centre of the magnet and it is **flat-shaped**, as expected.

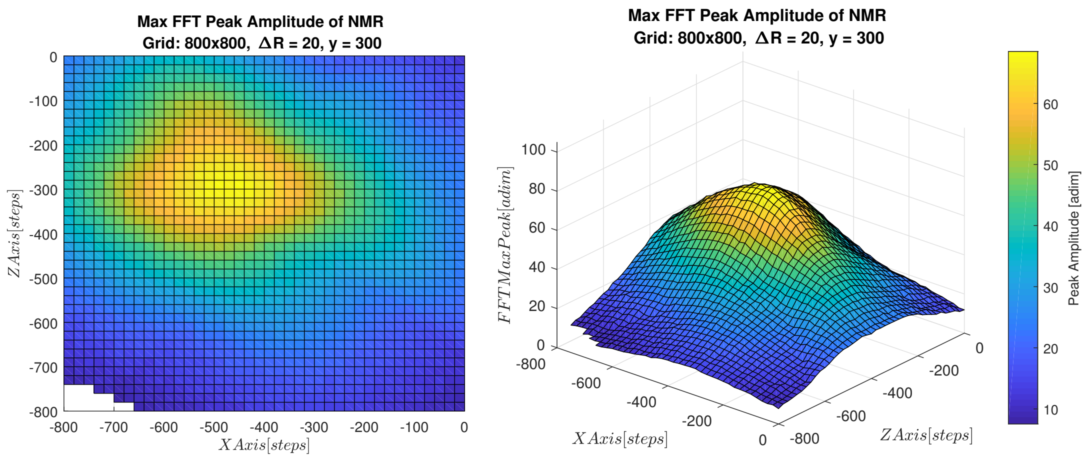

Figure 30: Space distribution of FFT peak values

4.4.2 Peak Analysis

In Fig.30 is shown the Space distribution of FFT Peak values.
Also in this case results are the expected ones: the plot shows a **bell-shaped** figure with a uniformity region in the centre.

4.4.3 3D Maps

Fig.29 and 31 show the same results of fig.29 but in a much more clear way. Moreover it is shown (in blue) the point with the maximum peak value. Using this reference it is possible to plot an accuracy map (Fig. 33): the **green area are the points with an accuracy below** 10^{-5} **respect to the Field Value of the blue point**.

To conclude, in Fig.34 the Uniformity and the Accuracy results are put together: In a **4x2 mm region the field is Uniform and Constant with accuracy of** 10^{-5} **T**.

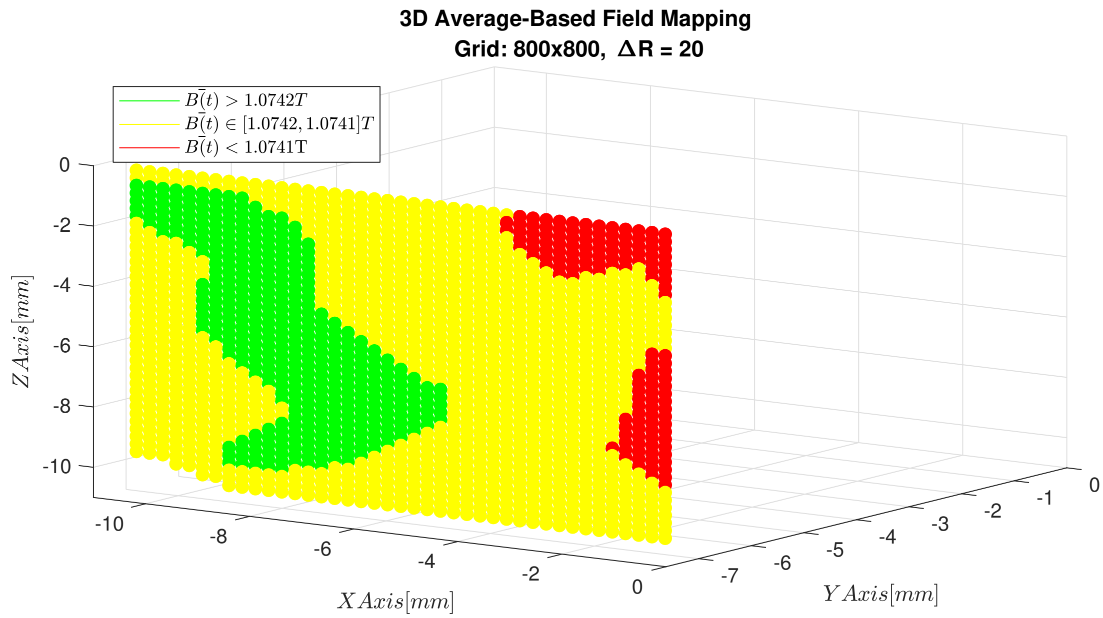

Figure 31: Field Map based on average value of the field

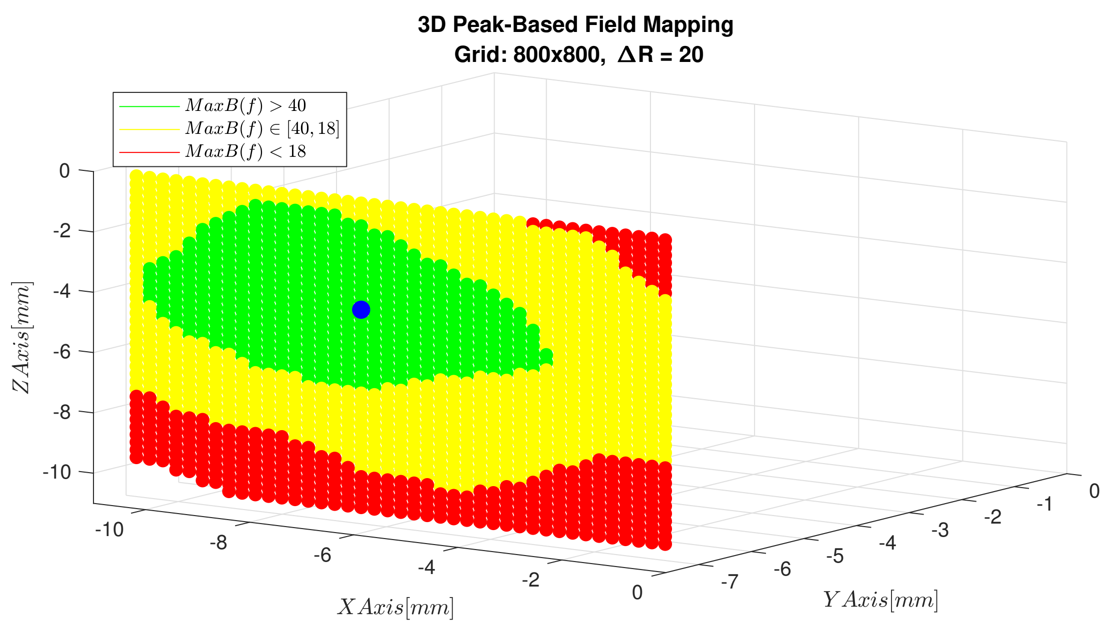

Figure 32: Field Map based on uniformity of the field

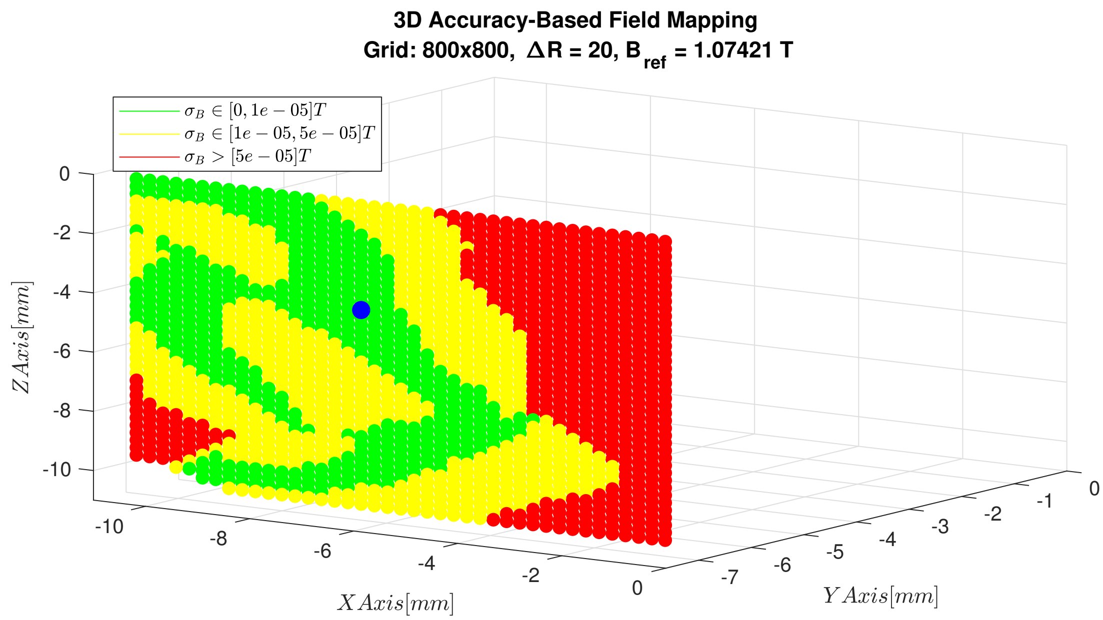

Figure 33: Field Map based on deviation of average value respect to a reference value

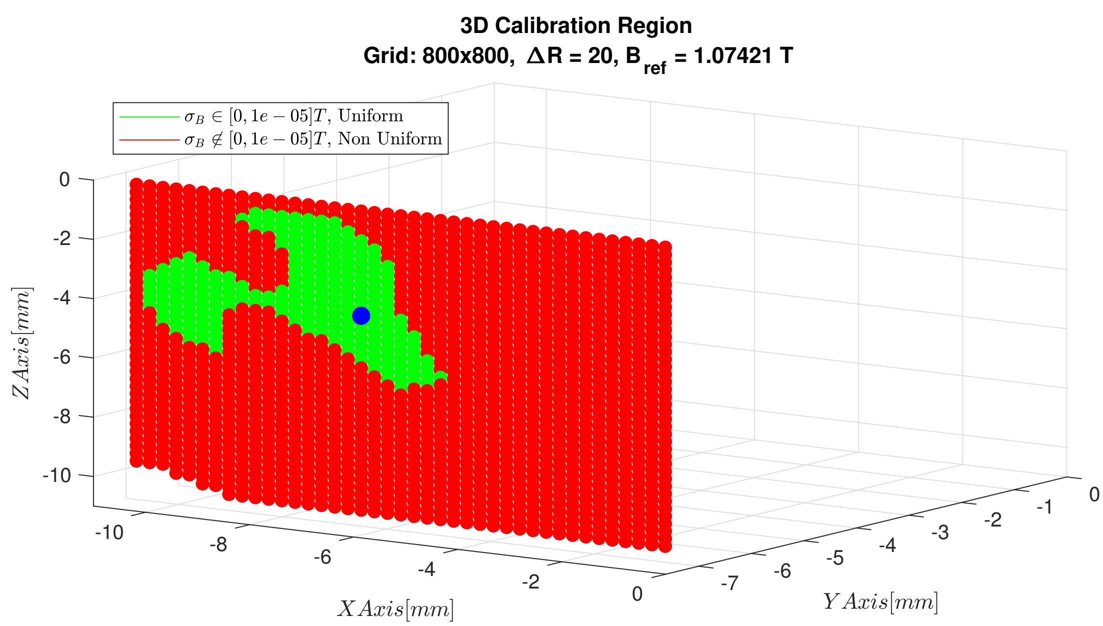

Figure 34: The uniform and constant region of a surface

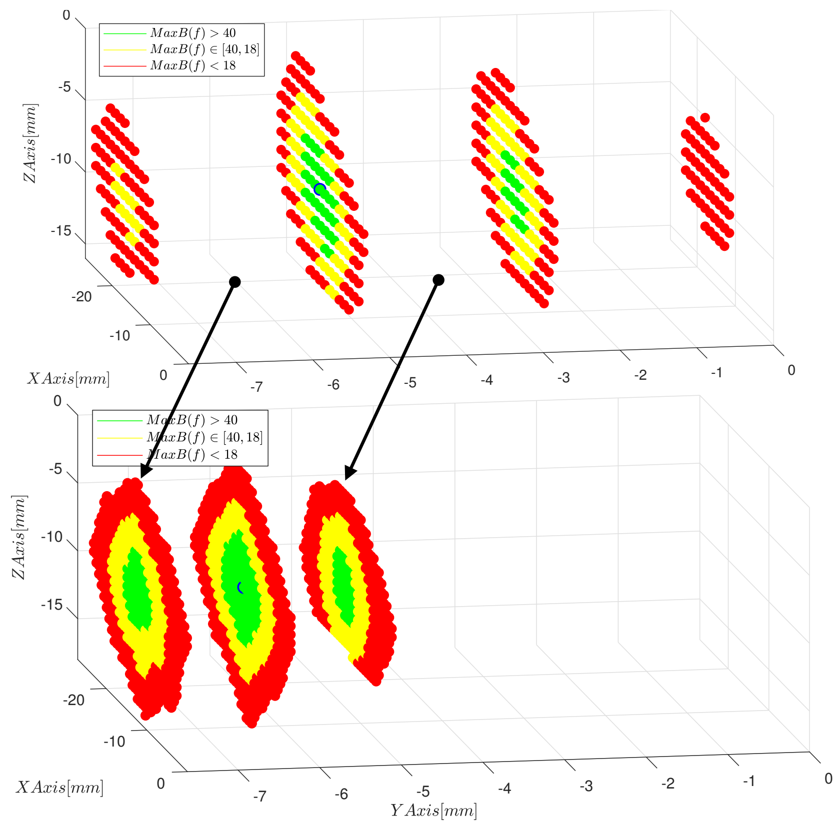

Figure 35: Maps comparison: $\Delta R = 100$ and $\Delta R = 50$

5 Conclusions

5.1 Lack of Precision

The Requirements of a Calibration Process are usually the following:

1. **Resolution** (related to the step size of a measure)
2. **Accuracy** (related to the error of a measure)
3. **Precision** (related to the repeatability of a measure)

Although the instrumentations of the Calibration Magnet's Plant respects resolution and accuracy requirement, a **lack of precision has been observed**.

In fact, as it is shown in Fig. 35, the **mapping of the week 6 and 7 are shifted on the Y Axis**.

There is not a clear explanation, but the possible causes of loss of precision are described in the next section.

5.2 Precision Loss Sources

A certain cause of precision loss is the **Y stage**: It has a **manual motion and an unknown backlash**.
This kind of control **introduce unbounded uncertainty** each time a new slice is sampled: an unbounded precision is the result.
Moreover:

- **No CAD Drawings are available** for experimental set-up: No accurate reference frames are documented.
- The XY stage has a **small moment of inertia on the X direction** that can introduce unbounded errors in the mapping

5.3 Suggestions

In order to calibrate the Hall Probes in a reliable way it is suggested to:

1. **Upgrade the mapping software** with
   - Robust handling of Hardware errors
   - Faster searching algorithm
2. **Review the XY Motion Stage** to gain precision, in particular:
   - an actuated Z stage is strongly suggested
   - more interest of the mechanics robustness should be considered

References

[1] Principles of NMR, By John C. Edwards, Ph.D
`http://www.process-nmr.com/nmr1.htm`