



# Calibration of a magnet used to calibrate Hall probes in Mu2e experiment

**Author**

Francesco Restuccia

**Co-worker**

Daniele Marchetti

**Supervisors**

Luciano Elementi

Thomas Strauss

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## Introduction

Goal of our internship at Fermilab was simulation and calibration of a magnet used for calibration of instrumentations. Magnet will be used to calibrate Hall probe in Mu2e experiment, probes are going to be used to measure absolute strength value and direction of magnetic field in solenoid detector. Due to magnetic field of detector solenoid in Mu2e experiment has to be known precisely (up to  $<10^{-4}$  T), the calibration magnet needs a very homogeneous magnetic field in the region of interest to obtain good calibration of probes.

Due to the nature of instrumentations, detector solenoid calibration will be performed using Hall Probe and Nuclear Magnetic Resonance Probes (NMR probes), the firsts to obtain 3D information on the field and the seconds to have a better resolution on absolute strength value (NMR probes measure only absolute strength value of the field, no 3D information are provided by this kind of probe).

Differently from NMR probes, Hall probes provide information on absolute strength value of magnetic field and 3D orientation, therefore it's needed a calibration both for the absolute field strength and for 3D orientation of the probe. Due to Hall effect strictly depends on temperature, in Hall probes calibration it's necessary to have a temperature monitoring to avoid incoherent results. Also, Hall probes calibration is repeated at several field strengths to confirm good calibration is reached.

First part of our work was to simulate a magnet geometry using COMSOL to understand challenges in obtaining a homogeneous magnetic field in the region of interest, which was 2 cm x 2 cm in the center of the calibration magnet. This area will be used to calibrate Hall probes, therefore was needed a spatial homogeneity of the field in order of  $< 10^{-4}$  T.

We simulated different cases, beginning with perfect ideal case. We moved than to real cases introducing non ideality in the geometry of magnet (skewed poles). Therefore, to improve magnetic field constancy in region of interest, we introduced shims, which are little pieces of metal stickled on pole's magnet, used to improve the magnetic field in some region. Goal of shimming procedure was to obtain a magnetic field shape similar to ideal case in skewed poles magnet case.

After simulations, we moved on the real magnet, we began with a course mapping of magnetic field to understand shape and strength. Afterwards, we

discover some challenges in magnetic field constancy during time, therefore we investigated it to understand causes and solutions.

In the meantime, I also tried to interface a 3D B-SENSOR made by Nikhef to a National Instruments interface. Goal was to readout the probe using LabVIEW software.

I implemented a script in LabVIEW to reach the goal, timings and output data was verified using an oscilloscope, but I didn't have any response from the board. I tried to speak with Nikhef to have support and understand what was the problem, but I didn't have any help from the company. Therefore, I had to abort further effort to concentrate on magnetic field mapping. (It could need a lot of time to understand what was the problem without any support from manufacturing company)

At the end of the internship, as explained in conclusions, we were able to obtain magnetic field spatial homogeneity of  $8.8 \times 10^{-5}$  T and temporal constancy of  $3 \times 10^{-4}$  T in the region of interest.

## Magnet configuration

Provided magnet was a GMW 3474-240/280 250mm electromagnet, that was a specific magnet used for calibration of instrumentations. Dimensions of magnet and poles are reported in figure 1:

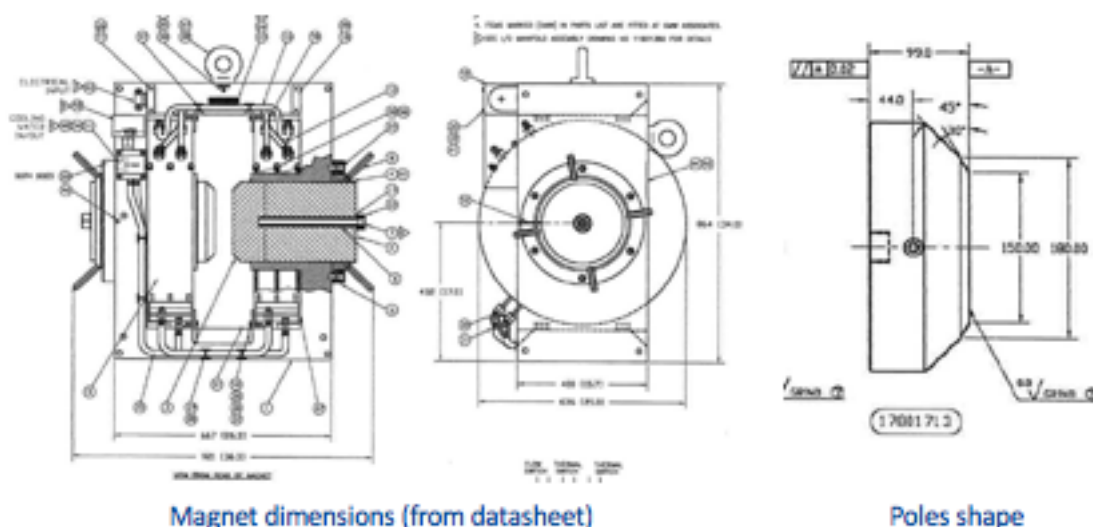


Figure 1: magnet and poles dimensions

As poles, were provided the configuration as in picture, we had this geometry because is the one guaranteed better results in term of homogeneity of the field

in central region. Dimensions shows that pole have 2 tape (first one of 45° degrees and second one of 30° degrees), therefore active region is reduced from 250 mm to 150 mm. Pole gap was configurable using proper handler, in every simulation and map we did, pole gap distance was 50 mm.

## COMSOL simulations

COMSOL is a finite element method (FEM) solver, in our case it solves Maxwell equations on a grid/mesh to obtain the magnetic field generated by the geometry.

Of course, depending on the type of simulation, is needed a trade-off between simulation time and accuracy. Sizes of shims used to compensate magnetic field in our application were very small, therefore was required very fine mesh to understand the effects on magnetic field.

Below are reported geometry and specifics of our simulated magnet, these specifications were used in every simulation we did in COMSOL, cross section of one single turn was extrapolated from number of turns per single coils and dimensions of the same (datasheet).

- Poles distance: 50mm
- Dimensions of the magnet: from datasheet
- Cross section of single turn:  $6.73 \times 10^{-5} \text{ m}^2$
- Number of turns: overall 360 per coil
- Overall resistance of a coil: between 0.11 – 0.13 W

In next paragraphs, are explained models and specifications of every simulation we did.

## 2D simulations

For 2D simulations, due to nature of the geometry, we couldn't apply any current to coils, therefore to understand the behave of the magnetic field we used magnetized poles, as in figure 2. Actually, this wasn't a realistic simulation, but we used it to understand magnetic field module on COMSOL in an easy to analyze environment.

We simulated 3 different cases, to see the shape of the magnetic field in:

- Ideal case
- Right pole rotated of 0.5 degrees (clockwise respect y axis) (skewed poles)
- Field compensation using shims

Following are reported simulated geometry, axis orientation and axis rotation

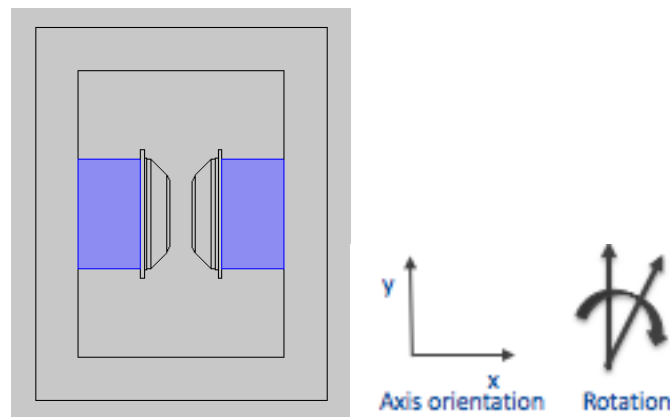


Figure 2: 2D model's geometry, magnetized poles in blue

Specs of the simulations as following:

- Current in coils: none
- Magnetization of poles: in x directions
- Material: all iron (air for the box)
- Type of mesh: extremely fine
- Computational time: 5 – 10 min

In ideal case simulation, we simulated 2 perfectly parallel poles, so was expected a high predictable shape of the field.

In right pole rotation simulation, we tried to simulate the shape of the magnetic field in a more realistic case, actually had two perfectly parallel poles wasn't a realistic situation.

Last simulation was about shimming procedure, which is used to compensate magnetic field in order to obtain a more homogeneous absolute value in the region of interest.

In 2D simulation we tried different geometry of shims, in figure 3 are reported the two bests configuration we found.

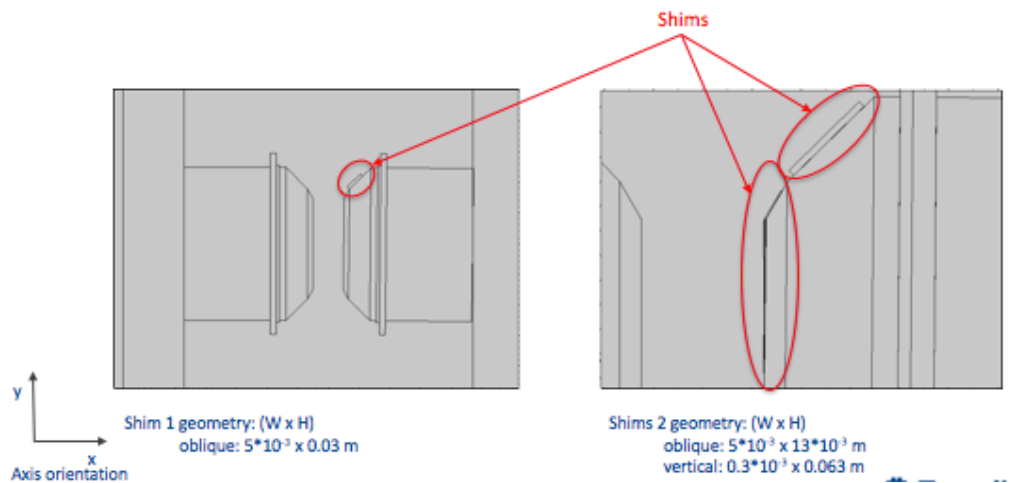


Figure 3: simulated configurations of shims

As explained below, the first configuration wasn't impact a lot on the magnetic field, instead with the second configuration we could reach a better homogeneity of magnetic field in region of interest.

To better understand results and to compare with datasheet, were used 3D cutlines in the center of the region of interest to plot the results.

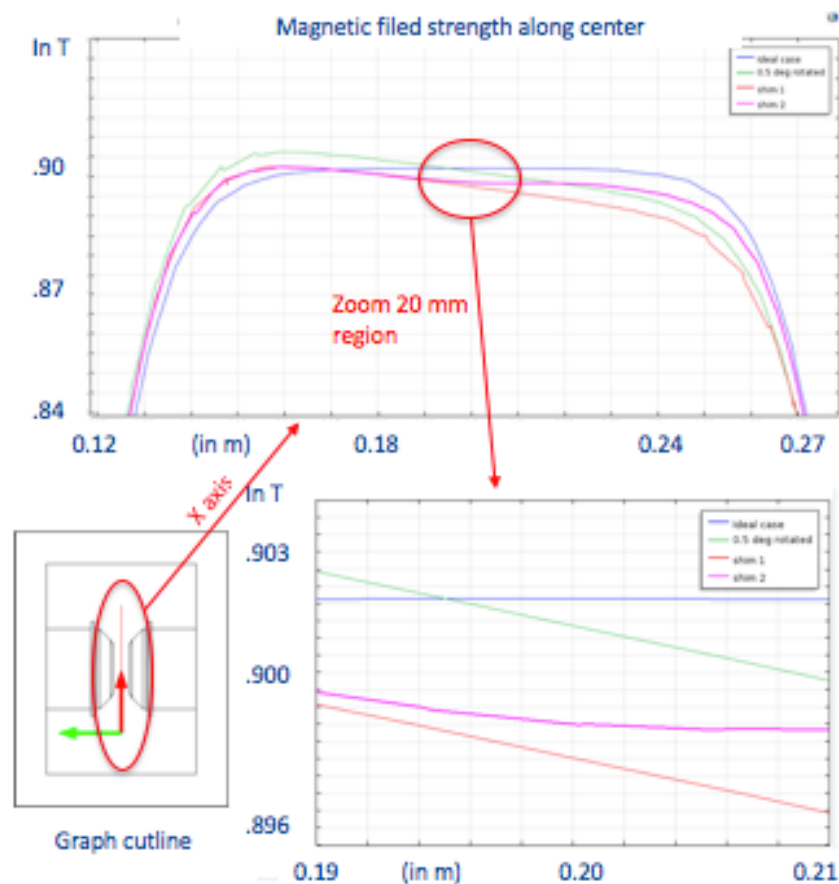


Figure 4: simulated magnetic field strength along cutline

In figure 4 are reported charts of all the region we investigated and a zoom to see the behave of the field in the region of interest (2cm x 2cm in center of the magnet), where:

- Blue line: ideal case, variations in order of  $10^{-4}$  T (due to mesh)
- Green line: skewed poles case, variations in order of  $10^{-2}$  T
- Orange line: 1<sup>st</sup> shims configuration, variations in order of  $10^{-2}$  T
- Magenta line: 2<sup>nd</sup> shims configuration, variations in order of  $10^{-3}$  T

## 2D axial symmetric simulations

After 2D simulations, we needed another symmetry to simulate current in coils, therefore we started to use 2D axial symmetric model.

In this specific case, due to nature of symmetry, we couldn't simulate shims, therefore this was only to understand the behave of magnetic field dependently on different current in coils (if current is provided in parallel, is possible to have different current in coils, due to different temperature between those, then different resistance). In figure 5 were reported implemented model and simulated magnetic field in this symmetry.

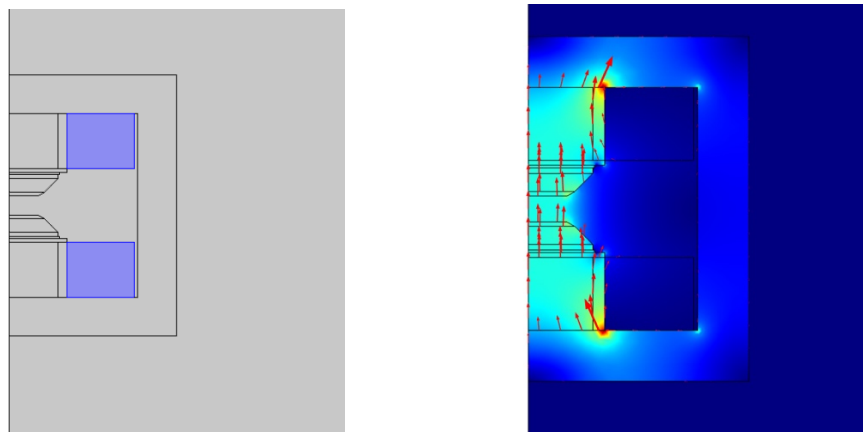


Figure 5: 2D axial symmetric model, copper coils in blue (left), simulated magnetic field strength (right)



Following specifications of 2D axial symmetric simulations:

- Coil's current: 100 A (simulated parallel and series supply)
- Single turn's section:  $6.73 \times 10^{-5} \text{ m}^2$  (extrapolated)
- Current density:  $\sim 742.94 \times 10^3 \text{ A/m}^2$  (from 100 A current)
- Magnetization of poles: none
- Type of modeling of coil: one single coil per side
- Material: all iron, coils of copper
- Type of mesh: extremely fine
- Computational time: 5 – 10 mins

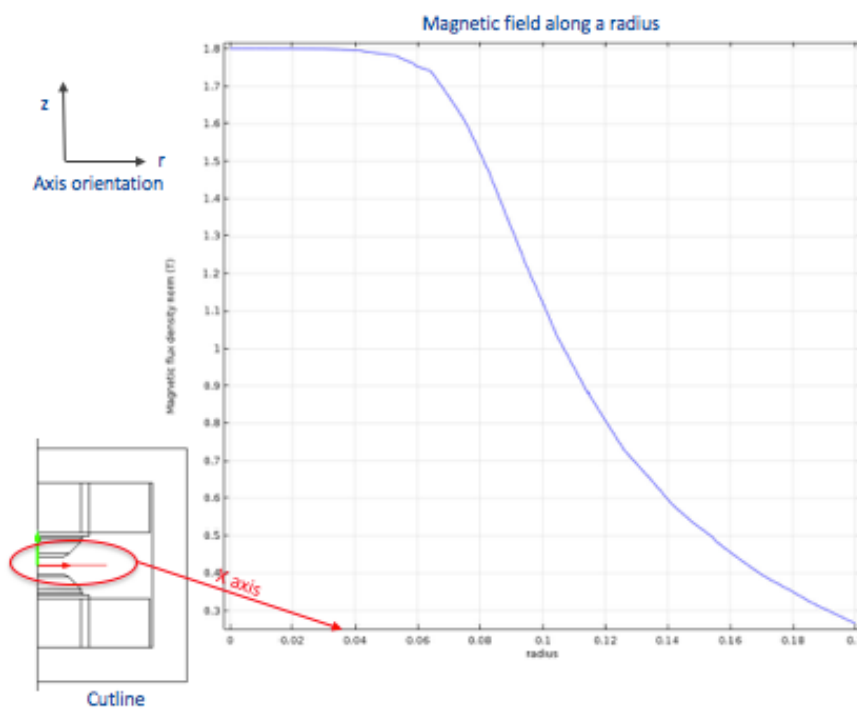


Figure 6: magnetic field strength along a radius

As possible to see in figure 6, the field shape was very similar to the shape of 2D ideal simulation, the absolute value of the peak was different due to different symmetry (magnet as a cube in 2D simulations, as a cylinder in 2D axial symmetric simulations). Investigation of different current's effect in coils due to different temperature showed variations in magnetic field in order of  $10^{-6} \text{ T}$ , therefore these variations are negligible for our study.

## 3D simulations

Finally, we simulated magnet using 3D simulations, these were the most realistic simulations we did. Even in this case, magnet was modeled on COMSOL using datasheet's dimensions.

As we did in 2D simulations, we simulated 3 different cases, to understand the shape of magnetic field in ideal case and rotated case (skewed poles, more realistic), the last simulation was to try to improve homogeneity of magnetic field in region of interest using shims. Geometry for ideal case was reported in figure 7.

Specifications as following:

- Coil's current: 100 A
- Type of supply: series (no different current per single coil)
- Magnetization: none
- Material: all iron, coils of copper
- Type of mesh: extremely fine (generally)
- Computational time: about a day (automated generated mesh), about 30 minutes using improved mesh

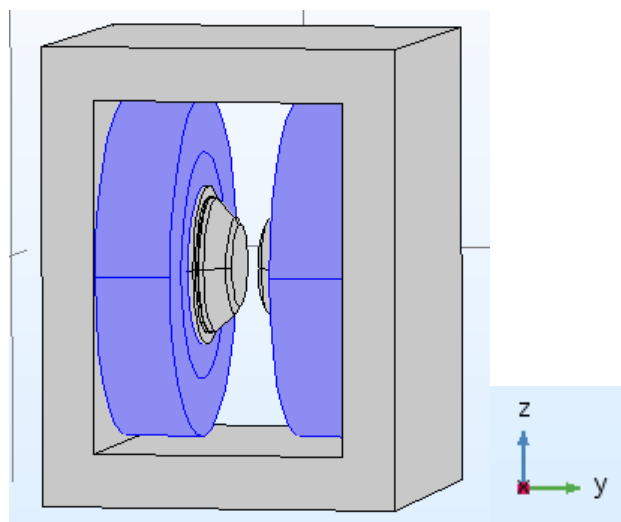


Figure 7: 3D model ideal case, copper coils in blue

During 3D simulations, was noticeable the effect of meshing on shape of magnetic field and simulation time. We tried before to simulate the field using COMSOL automated generated mesh (extremely fine), but that needed about a day to simulate without a high number of point calculated in the region of interest. Therefore we had a map of the field obtained by an interpolation of a restricted number of point.

Afterwards, we tried to improve the mesh for our goal, was put a box in the center of the magnet, then we built a custom mesh, as in figure 8. In this way we could obtain better results in term of number of point calculated in region of interest in very less time (about 30 minutes for the improved mesh respect about a day to simulate COMSOL automated generated extremely fine mesh).

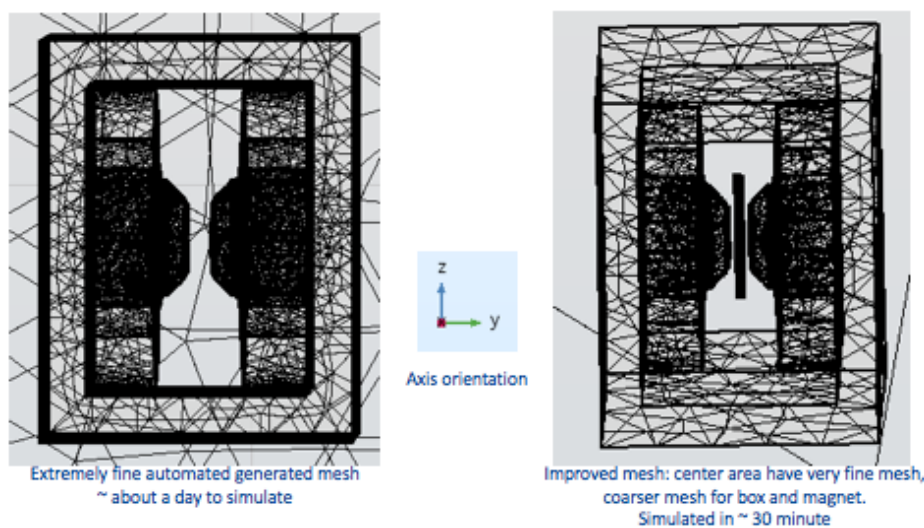


Figure 8: COMSOL automated generated mesh (left), built custom mesh (right)

In figures 9 are reported 2 chart of the calculated magnetic field in the ideal case (parallel poles), the first is a surface graph of XZ plane in the center of the magnet (green bars are the yoke), the second one are XY and YZ planes cut in the center of the magnet.

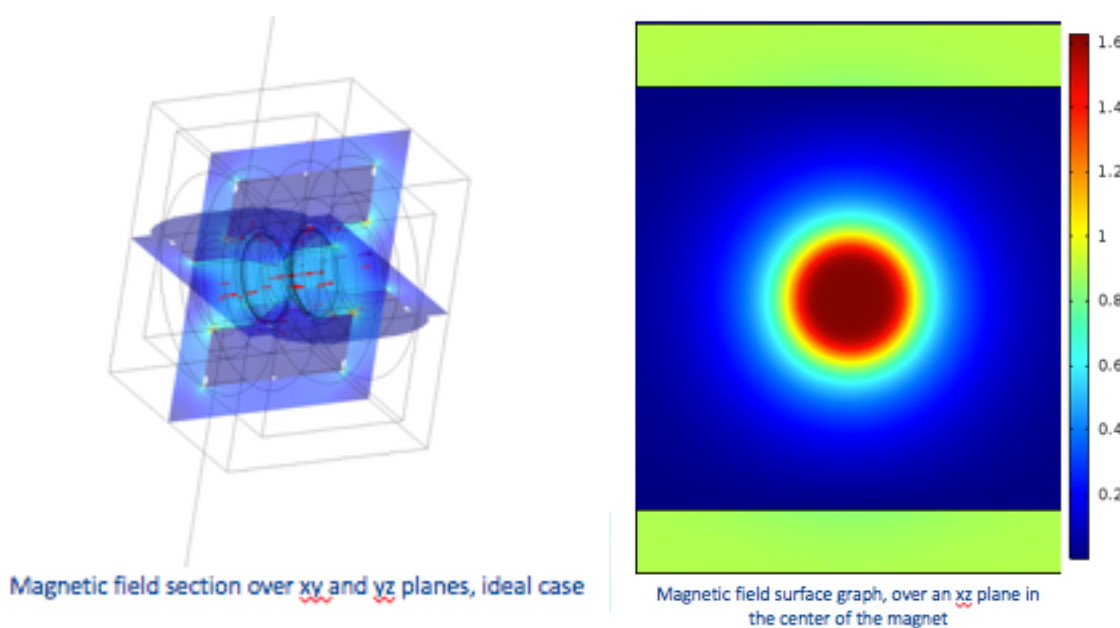


Figure 9: magnetic field strength over  $XY$  and  $YZ$  planes (left), over  $XZ$  planes (right)

To compare differences between three simulated cases (and also to compare results with datasheet), we needed to have different visualization of data (as in 2D simulations and 2D axial symmetric simulations), therefore was plotted magnetic field along 3D cutlines, as reported in figure 10-11.

Before, we simulated ideal and rotated case with automated generated extremely fine mesh, then was tried to improve magnetic field's homogeneity using shims. Tried 2 shims configurations: a rough configuration to understand the effects on the field (figure 10):

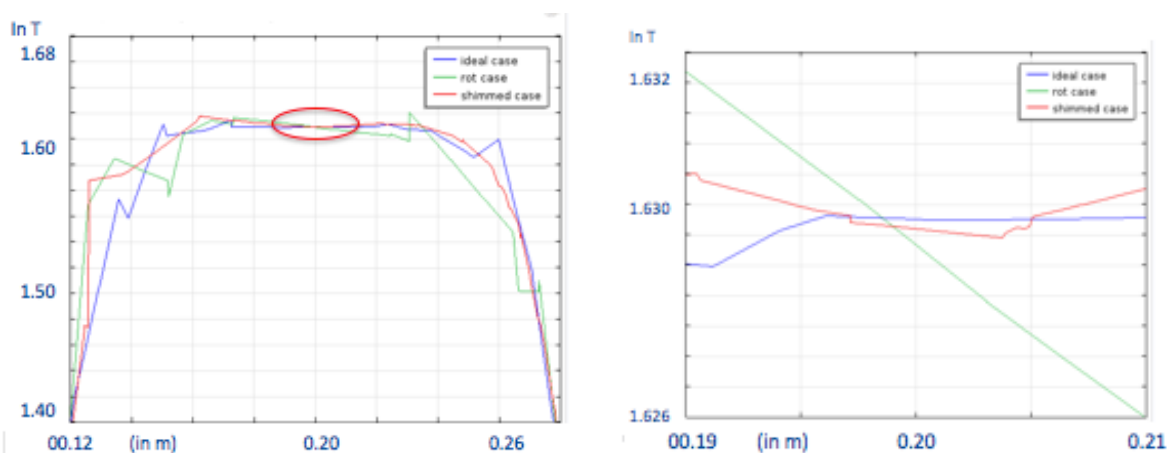


Figure 10: first configuration of shims, effect of not improved mesh is clearly visible

then was improved shims configuration and also the mesh. Were obtained the results as in figures 11:

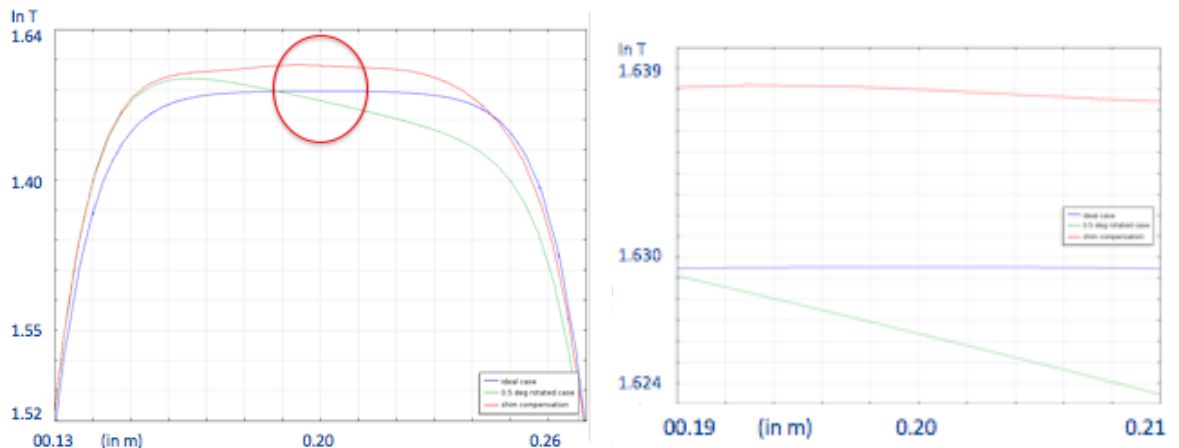


Figure 11: magnetic field along cutline, 2nd shims configurations and improved mesh. Zoom in region of interest (right)

In second configuration, thanks to improved meshing, lines are more continuous, due to a higher number of point simulated in the region of interest, therefore a better interpolation of data.

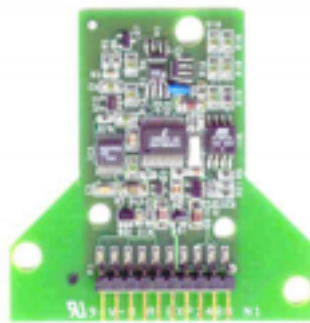
Also, is possible to see, better than before, that the improvement of the homogeneity of magnetic field in shimmed magnet is in order of  $10^{-4}$ .

Final comparison showed the different homogeneity of magnetic field in simulated cases:

- Blue line: ideal case, variations in order of  $<10^{-4}$  T
- Green line: skewed poles case, variations in order of  $10^{-3}$  T
- Orange line: compensation with shims, variations in order of  $10^{-4}$  T

## Reading out and Hall probe

Parallel task to mapping magnetic field on the magnet was trying to interface a Nikhef 3D Hall Probe to a National Instruments USB-8452 SPI/I<sup>2</sup>C interface. The goal was to readout the probe using National Instruments LabVIEW software. A picture of the probe is reported in figure 12.



Nikhef 3D B-Sensor

Figure 12

Probe was a Nikhef 3D B-SENSOR, over the board were 3 Hall probe sensors, 3 ADC (one for each sensor) and a microcontroller. Due to the structure of the board, protocol used to communicate was a custom SPI, something similar to an SPI bus (5 lines used from protocol: clock, data out, data in, chip select, ground). To readout a specific Hall probe sensor was needed to address it with a custom 3-4 bytes command path to microprocessor, than directly read results from probe (transparent microprocessor in readout step).

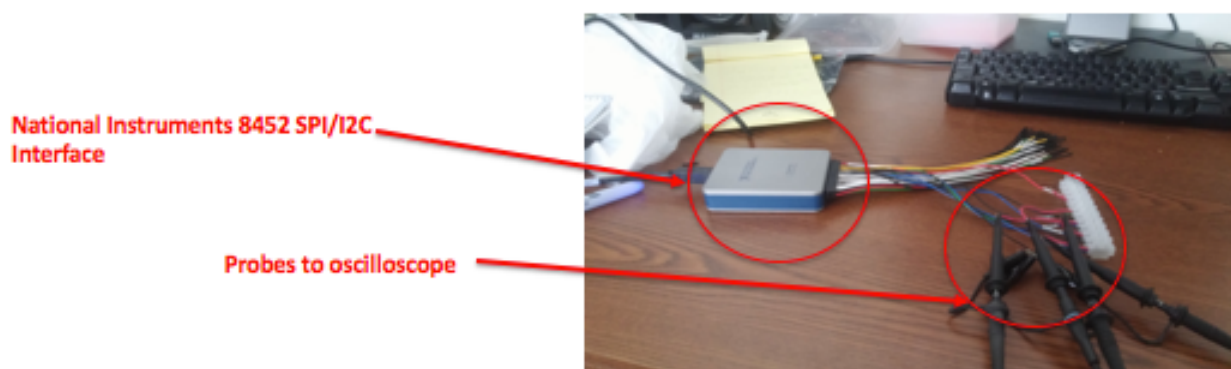


Figure 13: National Instruments 8452 SPI/I<sup>2</sup>C interface wired to oscilloscope probes

To achieve the results, I wrote a script in LabVIEW, as reported in figure 14:

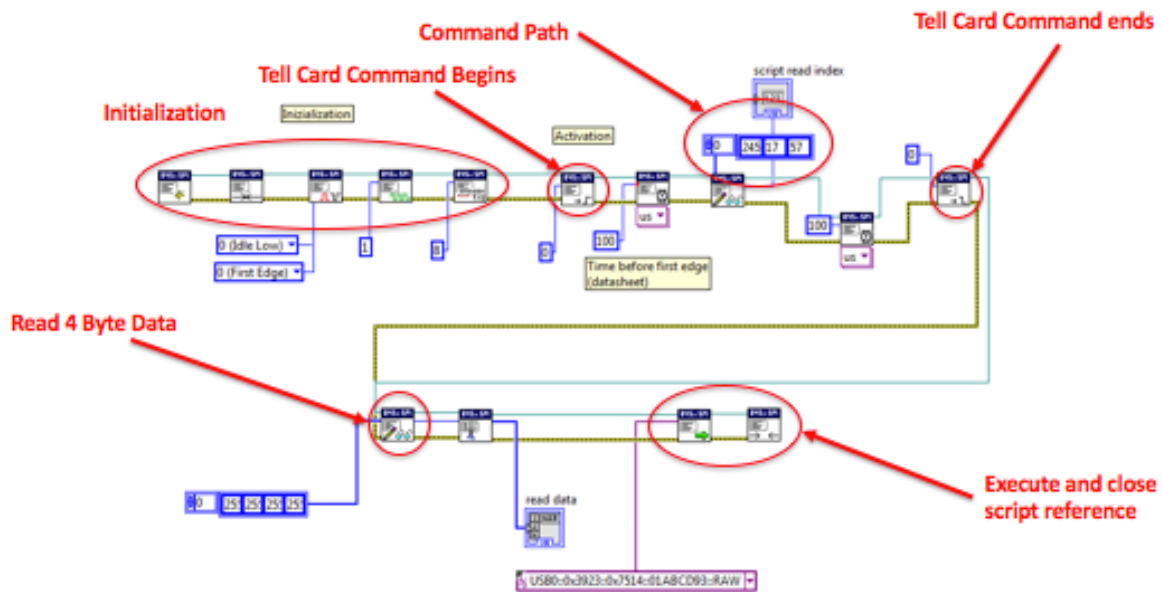


Figure 14: LabVIEW script used to readout the probe

In the beginning, was implemented the initialization of the script, then was put down Chip select line as a beginning of command path. Was waited 100 us as explained in datasheet before wrote the first byte, then was wrote the command path: first byte is a SYNC byte (from datasheet, used from board to check the goodness of communication), second byte is BS\_SELECT (also given by datasheet) and last byte is the number of the probe to interrogate. Afterwards, was put down Chip select line as end of command path and tried to read 4 bytes data from addressed probe.

After script building, I tried to connect a LeCroy WaveRunner oscilloscope to SPI the interface (as in figure 13) to check if timings and data was as expected as datasheet. Output from oscilloscope is reported in figure 15

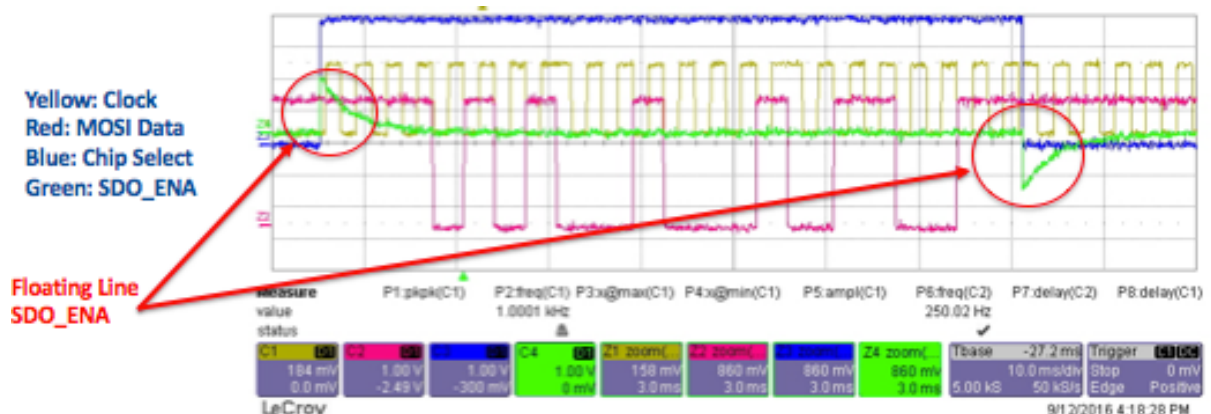


Figure 15: oscilloscope output

After confirm that timings and data were good, I tried to connect the probe to the interface. Was expected, as explained in datasheet, that SDO\_ENA (green line) rose up after Chip Select (blue line) felt down as response from the probe, but in figure 15 is possible to see that SDO\_ENA was a floating line.

Tried to understand what was the problem, changing timings and data wrote to the interface without any response from the probe.

Also tried to have support from Nikkef to understand what was the issue, without any response. In sight of this, I had to abort further effort and concentrate only in the mapping of the magnetic field, as in next paragraph.

## Moving to magnet: magnetic field mapping

After simulations step, we began to operate on the real magnet. Goal in this step was to characterize and stabilize the magnet to obtain a space homogeneity in order of  $10^{-4}$  T in region of interest.

Began with a coarse characterization of the field using NMR probe N. 5, then passed to a finer characterization using NMR probe N. 4.

Afterwards, we tried to face with discovered during mapping challenges to improve the homogeneity of magnetic field in region of interest.

## Instruments and robot setup

First step was to learn how to operate on magnet and instrumentations we needed. Following a little presentation of instruments:



Cooling water temperature panel

Water cooling temperature

Figure 16



Cooling water control panel, as in figure 16, was used to monitor magnet and power supply cooling water temperatures. Was possible to change the cooling water set-point to set magnet and power supply's regime working temperature. Set-point temperature is the point when control opened to external cooling circuit exchanger.

Metrolab Teslameter PT 2025 NMR probe, used to map magnetic field. Due to the nature of instrument (based on Nuclear Magnetic Resonance), we had to choose the proper probe dependently on absolute field strength to measure. Mostly used NMR probe N. 4 (0.4 – 1.05 T), but in firsts characterizations we used NMR probe N. 5 (1 – 1.2 T) (probes are more accurate in the high region of their working interval).

Also used 2 DMM (digital multi meter) to monitor supply current/voltage in coil's magnet. Voltage was read directly from input voltage of magnet; current reading was provided by Danfysik Saturn Transducer (voltage value associated with coil's current value). Transducer was a part of initial setup of magnet, was also a feedback used from power supply to stabilized coil's current.

In the beginning, we used a Keithley 2001 (resolution of  $10^{-4}$  V) as DMM to monitor current and an HP 3457A (resolution of  $10^{-5}$  V) as DMM to monitor supply voltage. Afterwards, in order to improve the resolution of measure, we borrow an Agilent 3458A DMM (resolution of  $10^{-6}$  V).

To move NMR probe along magnet, we used a 2 axis (X and Z) robot, directions of axis were as in figure 17.

Was mapped the field along parallel line over x axis. Combining different lines of measure at different Z coordinate we obtained a mesh (map).

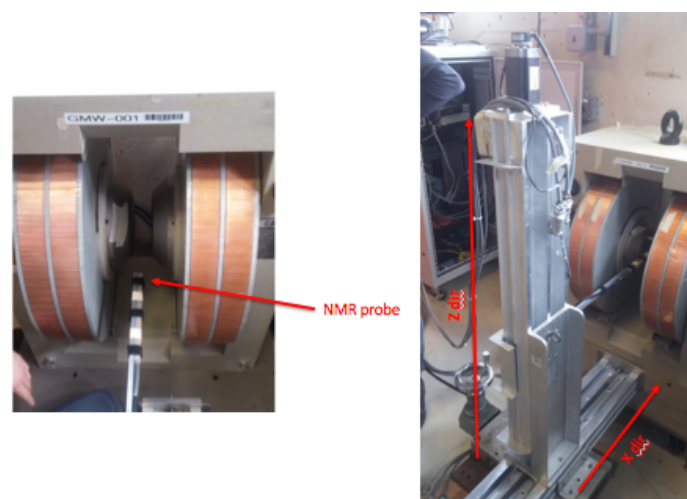


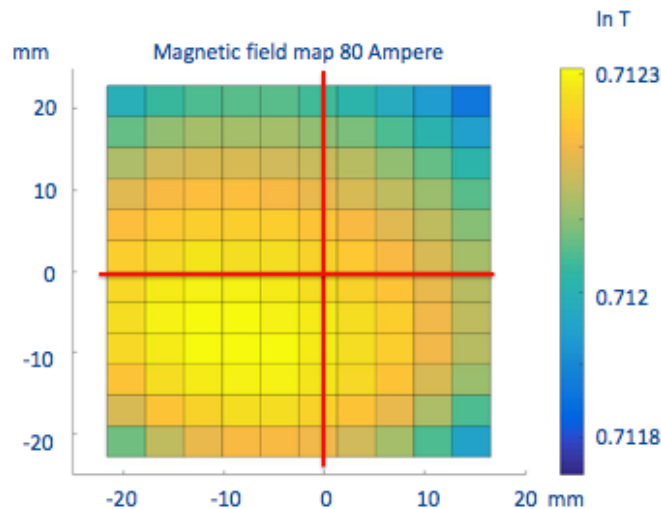
Figure 17: fixed NMR probe (left) and used 2 axis robot (right)

## *Magnetic field mapping: skewed poles*

In the beginning, we did different measure using NMR probe N.5 to understand the behave of the field (NMR probe N.4 was broken in the beginning of mapping procedure), then we moved to NMR probe N.4 to have more accurate measure of the field strength.

Following is reported the first significant map of the field, specifications was:

- Coil's current: 80 A
- Water cooling set-point: 85° F
- NMR probe N.4 (0.35 – 1.05 T)
- HP 3457A DMM for voltage supply measurements
- Agilent 3458A DMM for coil's current measurements



*Figure 18: first magnetic field strength map*

After first map, as in figure 18, was possible to see that the magnetic field peak wasn't correspond with the geometric center of the magnet. COMSOL's simulations explain this phenomenon with skewed poles. Measuring of gap size using spacers confirmed the skew in order of 1 mm between two poles.

Afterwards, to correct the skew and obtain more parallel coils and poles we used 3 spacers as reported in picture.



*Figure 19: used spacers*

We obtained a map of magnetic field as in figure 20. Using skew correction, the field peak moved near the geometrical center of the magnet, also we could obtain a better spatial homogeneity of absolute value of the field, from  $1.3 \times 10^{-4}$  T to  $8.8 \times 10^{-5}$  T (in the region of interest).

Black box in figure 20 represents region of interest (2cm x 2 cm in the center of the magnet), the intersection of lines is the geometrical center of the magnet.

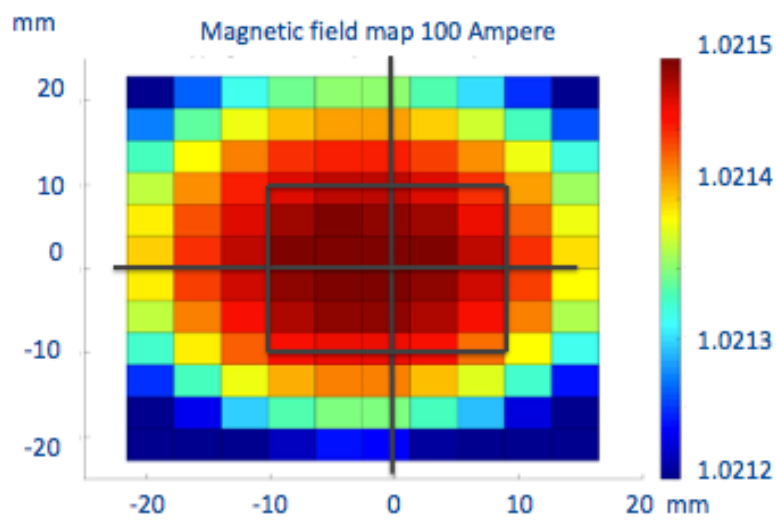


Figure 20: magnetic field map after skew correction

After magnetic field mapping, we could compare results from measurements and simulations. Comparison is reported in figure 21, absolute value of magnetic field was normalized due to different specifications of simulations, red box in COMSOL simulation chart is the region of interest.

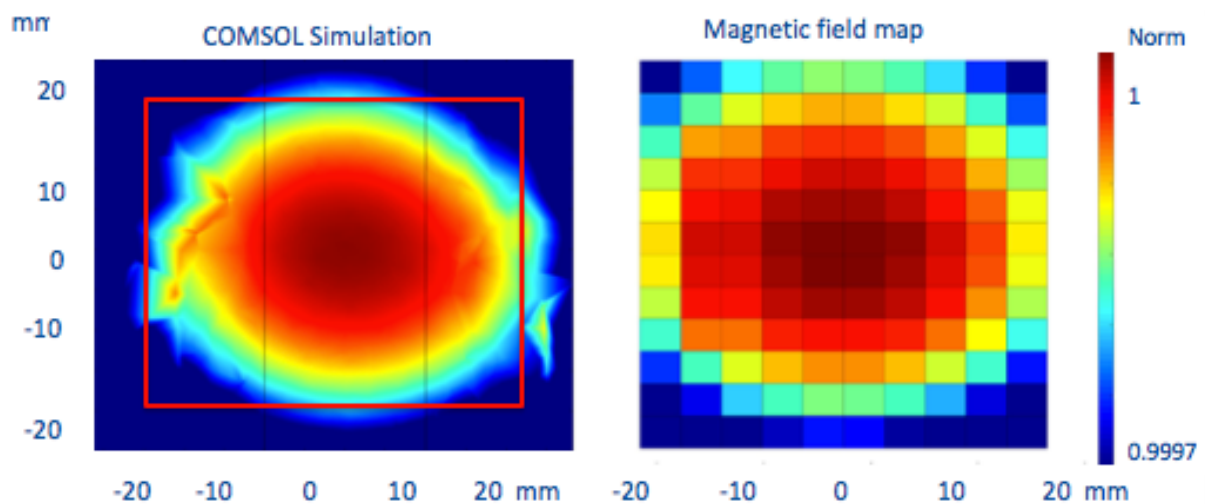


Figure 21: COMSOL simulated magnetic field (left) VS magnetic field map (right)

From comparison is possible to see that shapes are very similar, we could conclude COMSOL simulation was a good starting point to understand how was the magnetic field for our geometry in ideal and real cases.

### Discovered challenges, improvements:

After this trance of mapping, was possible to saw that spatial variations were in order of  $8.8 \times 10^{-5}$  T (good for given specifications), but also that temporal variations in absolute value of magnetic field was consistent (in order of  $10^{-3}$  T). Therefore, we tried to investigate this phenomenon making some improvement:

- Increased resolution on current reading using Agilent 3458A DMM (resolution of  $10^{-6}$  T in current reading);
- Saw hysteresis effect, therefore we introduced Degauss procedure to avoid it, as explained below, and introduced a ramping profile in current to increase repeatability;
- Changed the cooling circuit temperature set-point to study the effect on magnet and power supply (same cooling circuit). Set-point was changed from 85° F to 100° F.

Degauss procedure is a procedure used to avoid the memory effect of pole's previous magnetizations (hysteresis), to obtain the goal is needed to set different positive and negative current until reach a current of 0 Ampere. An example of Degauss procedure we used is reported in figure 22

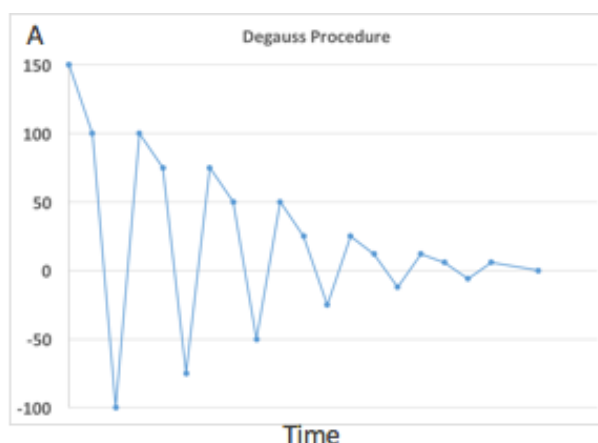


Figure 22: examples of Degauss procedure

Started from 150 Ampere, went down to 100 A and invert the polarity of the current to reach -100 A in coils. Afterwards, current was re-set to a positive value of 100 A and so on until reached 0 A.

After Degauss procedure, was reached the required coil's current using a ramping profile to avoid overshoot.

Results in temporal constancy after improvement are visible in figure 23, was monitored a single point in the geometrical center of the magnet along 3 days. During night we had to shut down the magnet, therefore every day before took measure was needed to wait magnet to reach regime point.

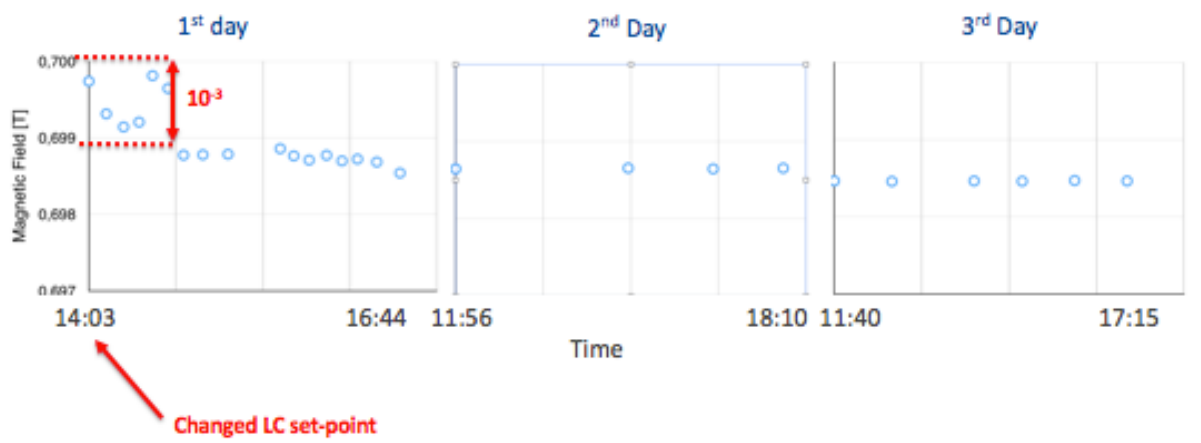
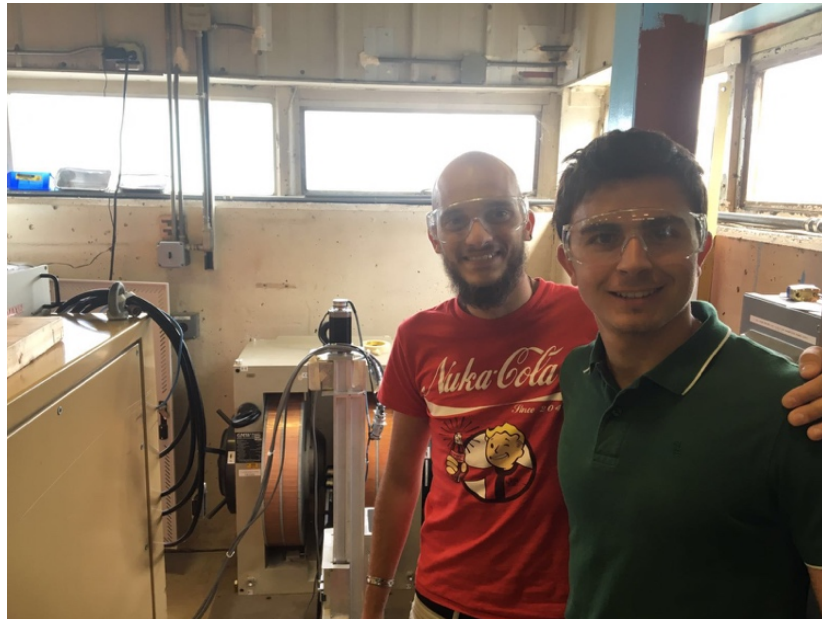


Figure 23: single point's magnetic field strength during 3 days mapping

Set-point was changed at 14:03 of the first day, is possible to see variations in order of  $10^{-3}$  in absolute value of magnetic field for the first 45 minutes after changing. Afterwards, the magnet reached a stable point, we could see variations in 3 days' measurements in order of  $3 \times 10^{-4}$  T, as possible to see in the same figure.

## Conclusions



*Figure 24: Me (left) and Daniele Marchetti (right)*

After the 2 month working on this project we could reach some interesting conclusion. We saw that COMSOL simulations was really helpful in understanding the magnetic field shape for a given geometry and a good beginning point to understand how to calibrate magnet and to obtain field homogeneity in the region of interest. Also, was a good exercise to have a starting point for real shimming of the magnet, in fact in simulations we could obtain a spatial homogeneity in shimmed magnet (skewed poles) of the field in order of  $10^{-4}$  T (similar to homogeneity of ideal case, due to effect of meshing).

During magnet mapping, we could see an initial spatial uniformity of  $<10^{-4}$  T in the center region of interest (2 cm x 2 cm)(without shimming), but we also saw, after some map, unstable absolute field value over time (about  $10^{-3}$  T shift). Investigations showed that power supply wasn't stable enough. To improve time constancy, we tried to change cooling water temperature set-point, reaching an improved stability in order of  $10^{-4}$  T. After this results, we understand that power supply was the main cause in the temporal variations of magnetic field, therefore we reach that power supply needs to be stabilized further in order to improve stability over time.

Magnet was not shimmed (as was in the first time plan) as we had to face with unstable time variations in magnetic field, therefore we investigated the source of time variations in detail during our program.