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

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Ex labore fructus

Introduction

- Magnet will be used for calibration of the Hall probes in Mu2e experiment
- One needs a very homogeneous magnetic field to obtain a good calibration of the probes
- Solenoid calibration will be performed with Hall probes and nuclear magnetic resonance probes (NMR)
- NMR probe measures the absolute field strength, no 3D information
- Hall probes need calibration for their absolute field strength and 3D orientation
- The Hall probe calibration is repeated at several field strengths
- The calibration needs to be very well understood ($\ll 10^{-4}$T), the homogeneity needs to be uniform, little pieces of metal help to shape the field (shims)

Overview

- **Simulation of magnetic field using COMSOL**
- **Instrumentation**
- **Measurement of magnetic field**
- **Improvement and discussion**

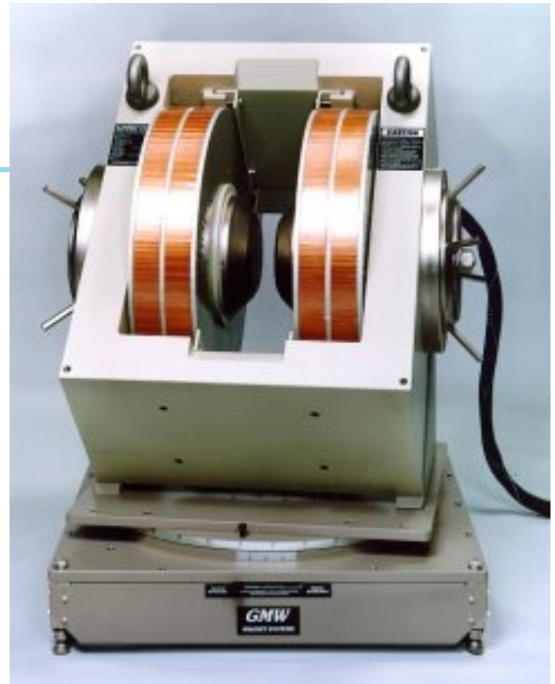
Our goal

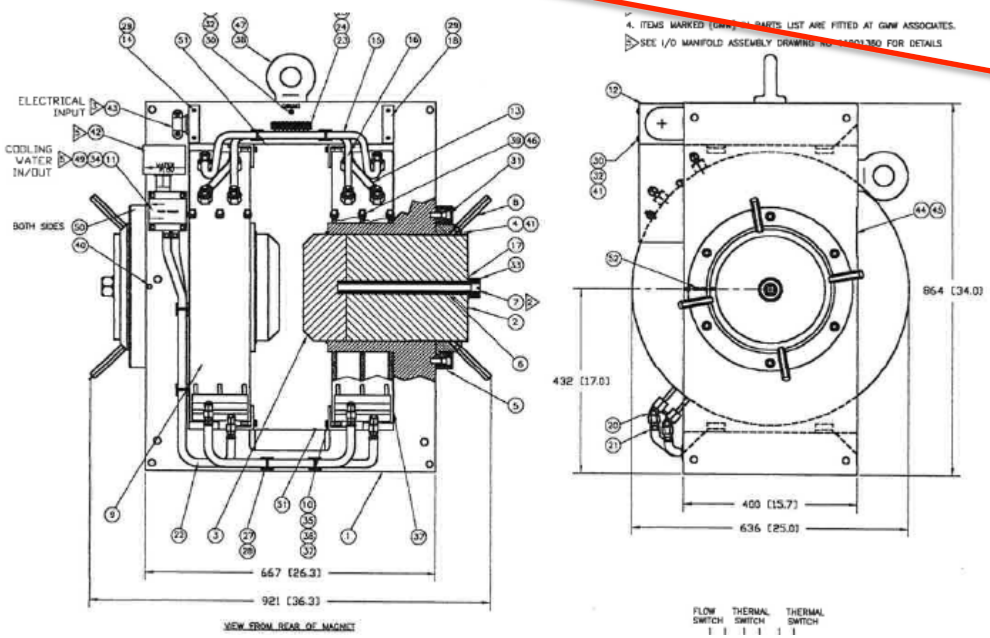
- Obtain a homogeneous magnetic field in the center of the magnet
- Up to << 10^{-4} precision of magnetic field in the center of the magnet

→ challenging!

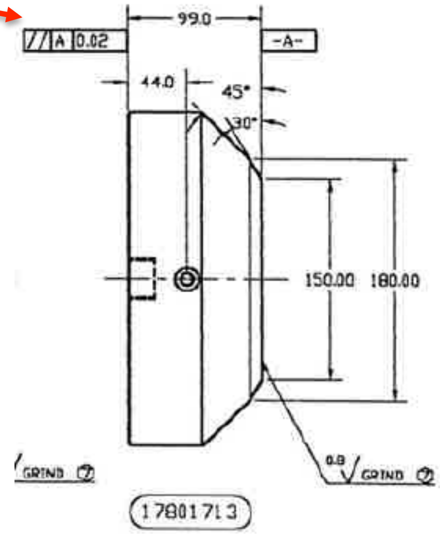
The magnet configuration

- Model: GMW 3474-240/280 250mm electromagnet
- Shape of pole as in figure, selected for high constancy of the field



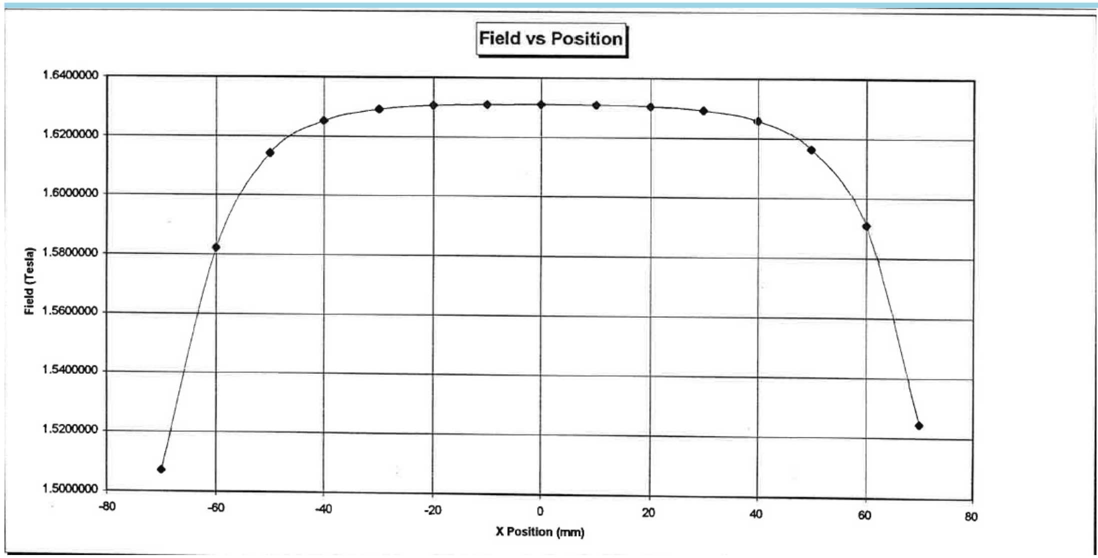


Magnet dimensions (from datasheet)



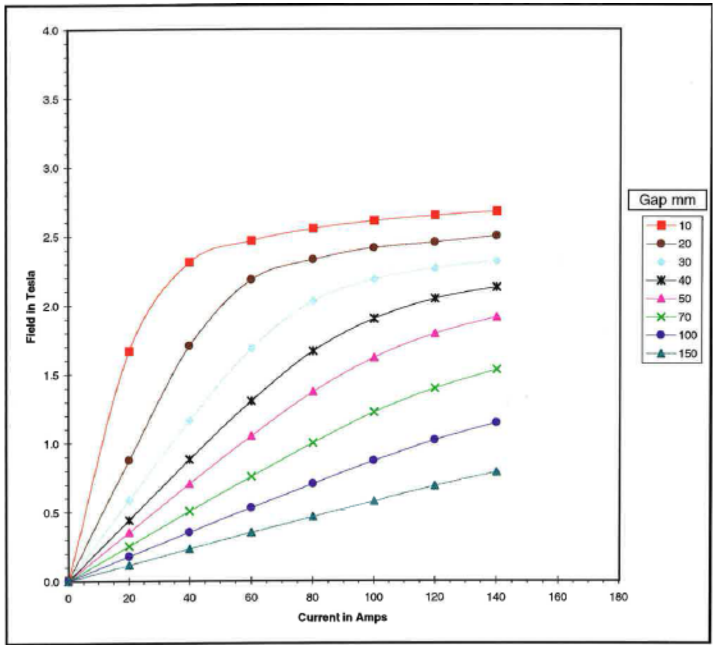
Poles shape

…Challenges (ideal case vs reality)



Magnetic field strength VS position 150mm pole, 100 A over coils, 50mm pole gap

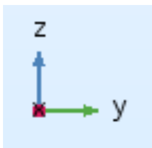
- Rotation of one pole can cause a variation in the uniformity of the field (main problem)
- Different currents between 2 coils due to different resistance if coils operate in parallel (in series, current is the same)
- Compensation can be made using shims (little pieces of metal applied on poles)



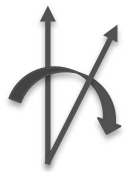
Magnetic field VS current 150mm pole

COMSOL Simulations: Overview

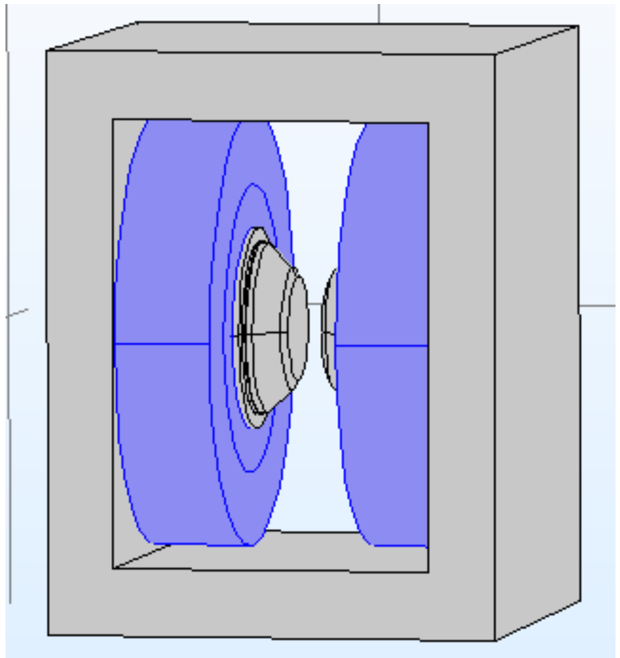
- Finite Element Method: Solve Maxwell equations on a grid/mesh to obtain the magnetic field
- Trade-off between simulation time and accuracy (finer mesh)
- Small sizes of shims requires very fine mesh
- 2D, 2D axial symmetric and 3D simulations
- Simulated three cases:
  - Ideal case
  - Right pole rotated of 0.5 degrees (clockwise respect y axis)
  - Field compensation using shims



Axis orientation



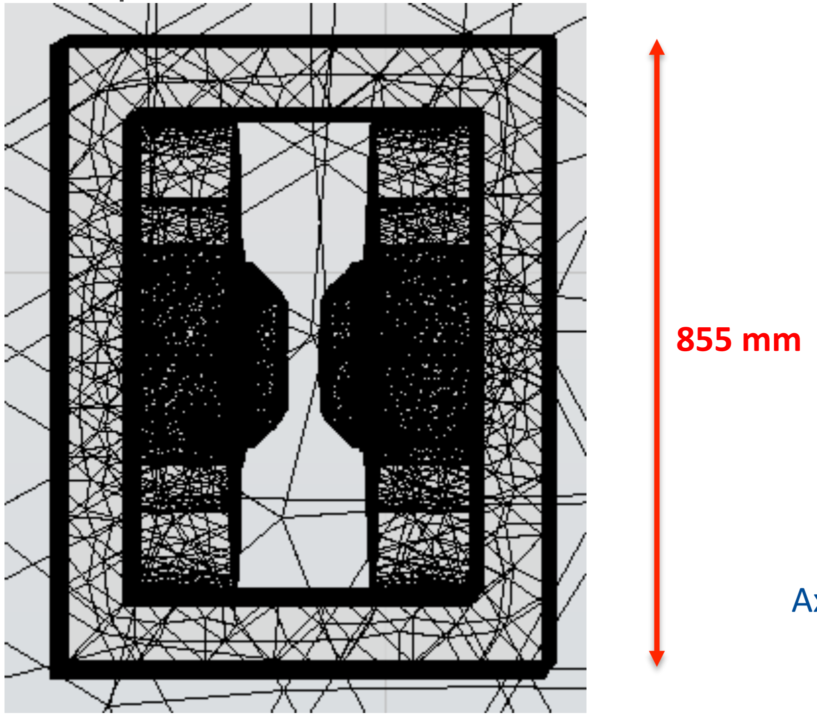
Rotation



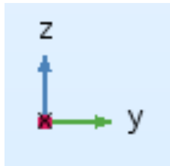
3D geometry in COMSOL, evidenced copper coil (blue)

3D Simulation: Meshing

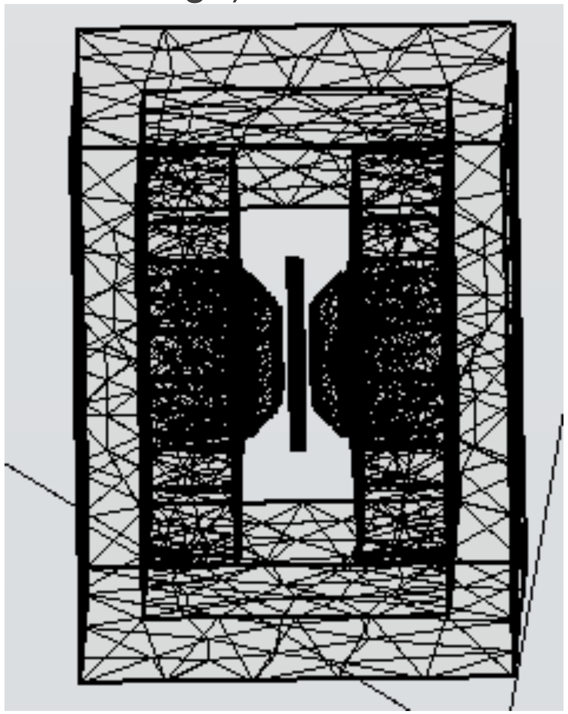
- In simulations the performance strictly depends on the type of used mesh
- Tradeoff between performance and accuracy
- Improved the mesh to obtain better results in less time (restricted range)



Extremely fine automated generated mesh
~ about a day to simulate

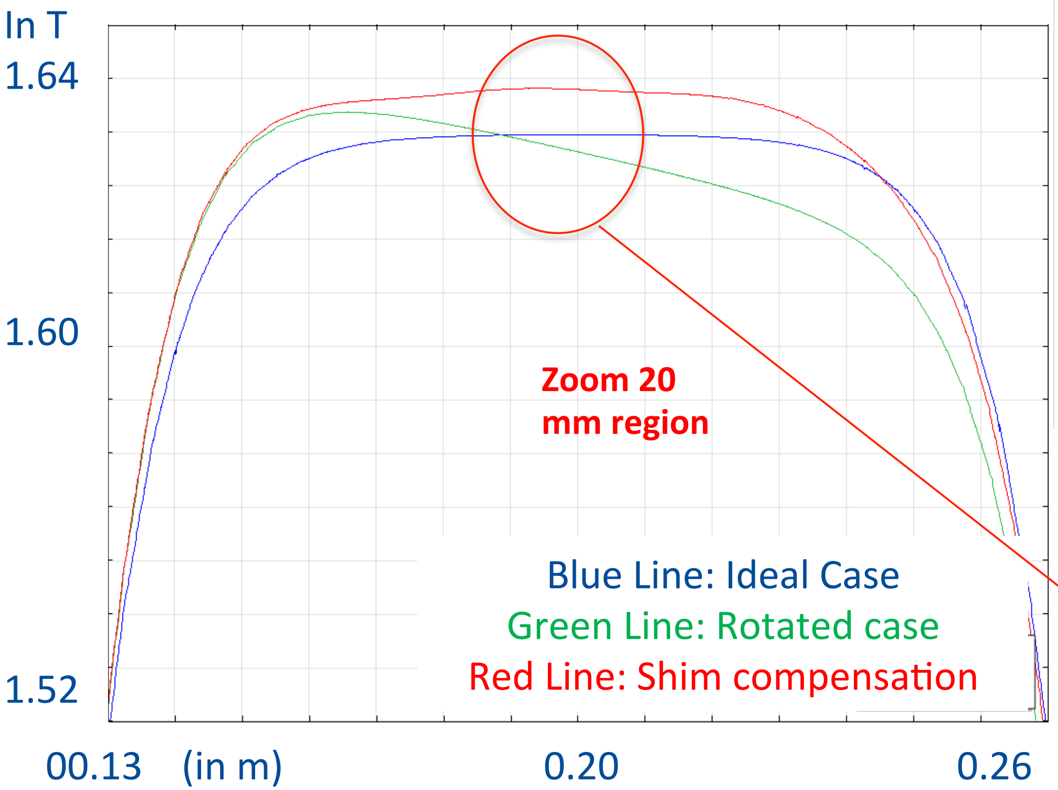


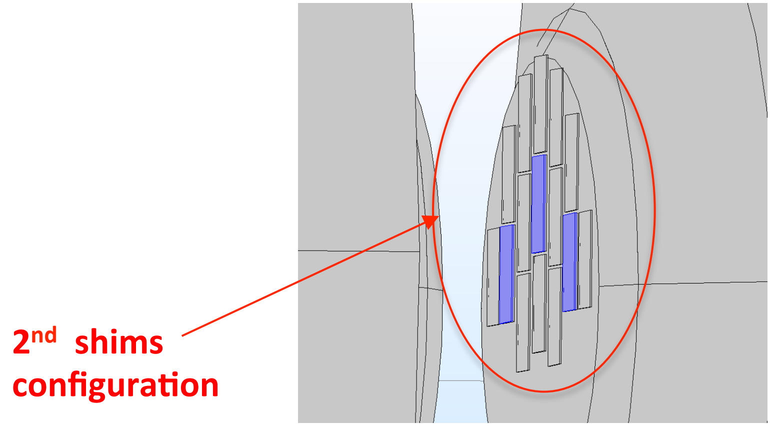
Axis orientation



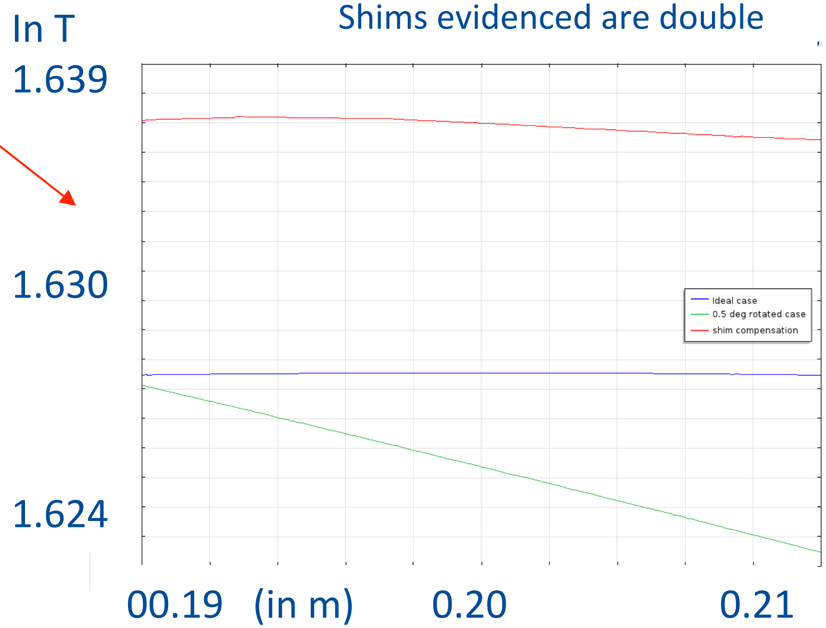
Improved mesh: center area have very fine mesh, coarser mesh for box and magnet. Simulated in ~ 30 minute

3D Simulation: Ideal VS rotated VS comp. with shims



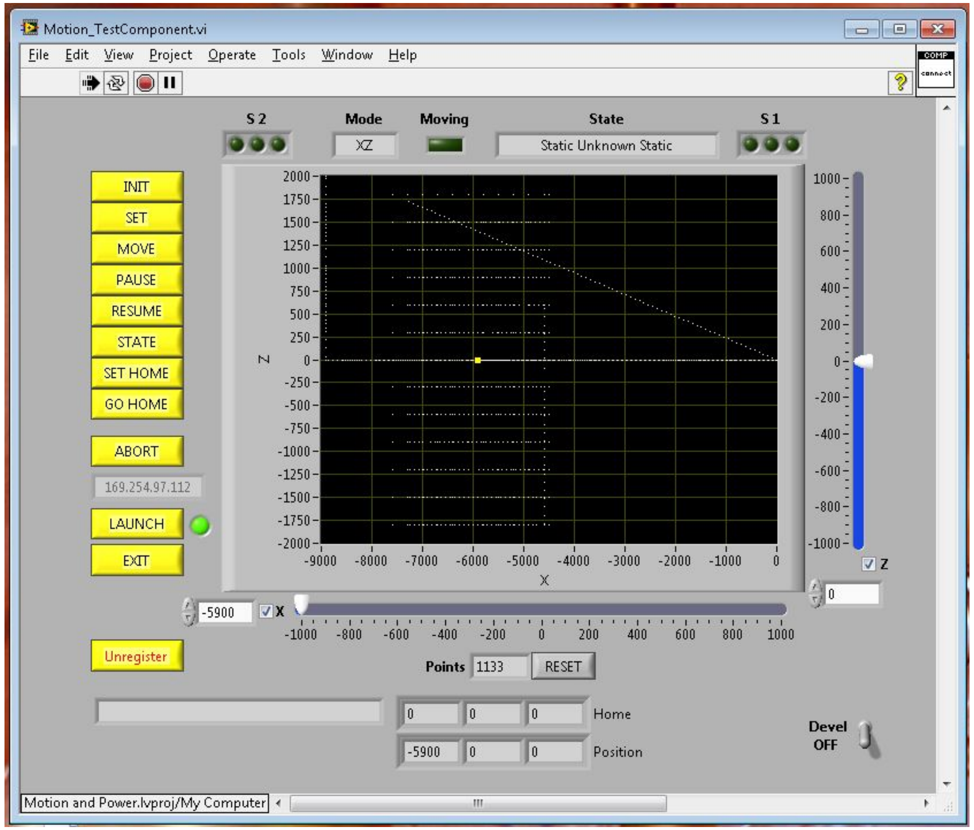


Shims evidenced are double



- Cutline along z axis
- Improved mesh
- Obtained a more constant field in the central region, as we can see in figure

Moving to instrumentation… reading out a Hall Probe



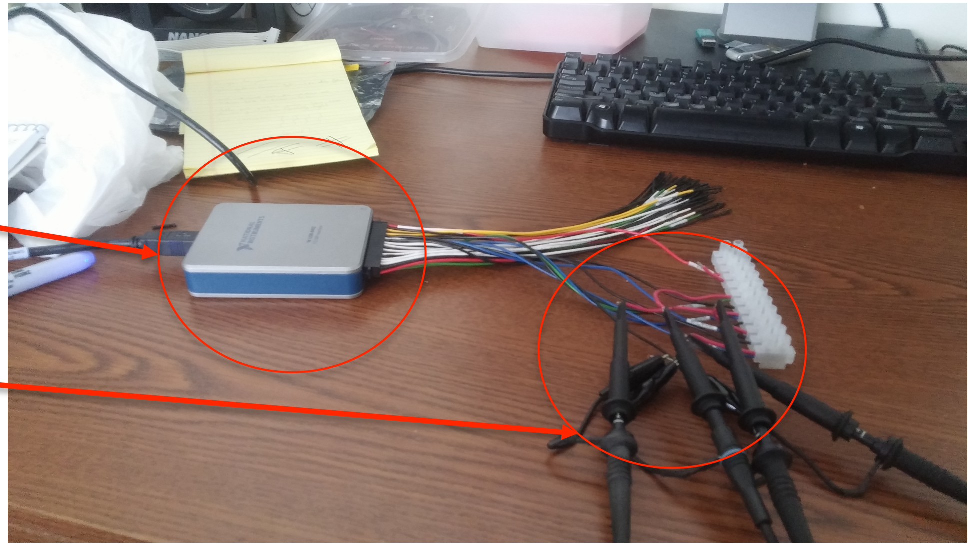
LabVIEW interface used to move 2D axis motor

2 Axis motor used to map the magnet

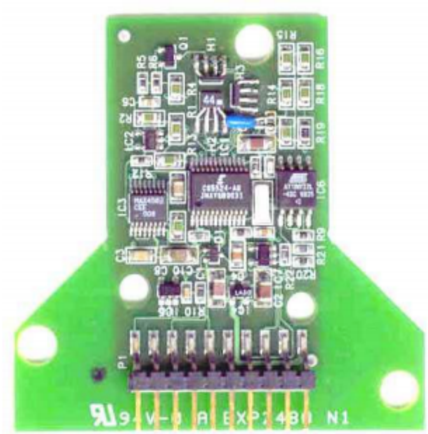
3D Hall probe SPI interface

National Instruments 8452 SPI/I2C Interface

Probes to oscilloscope

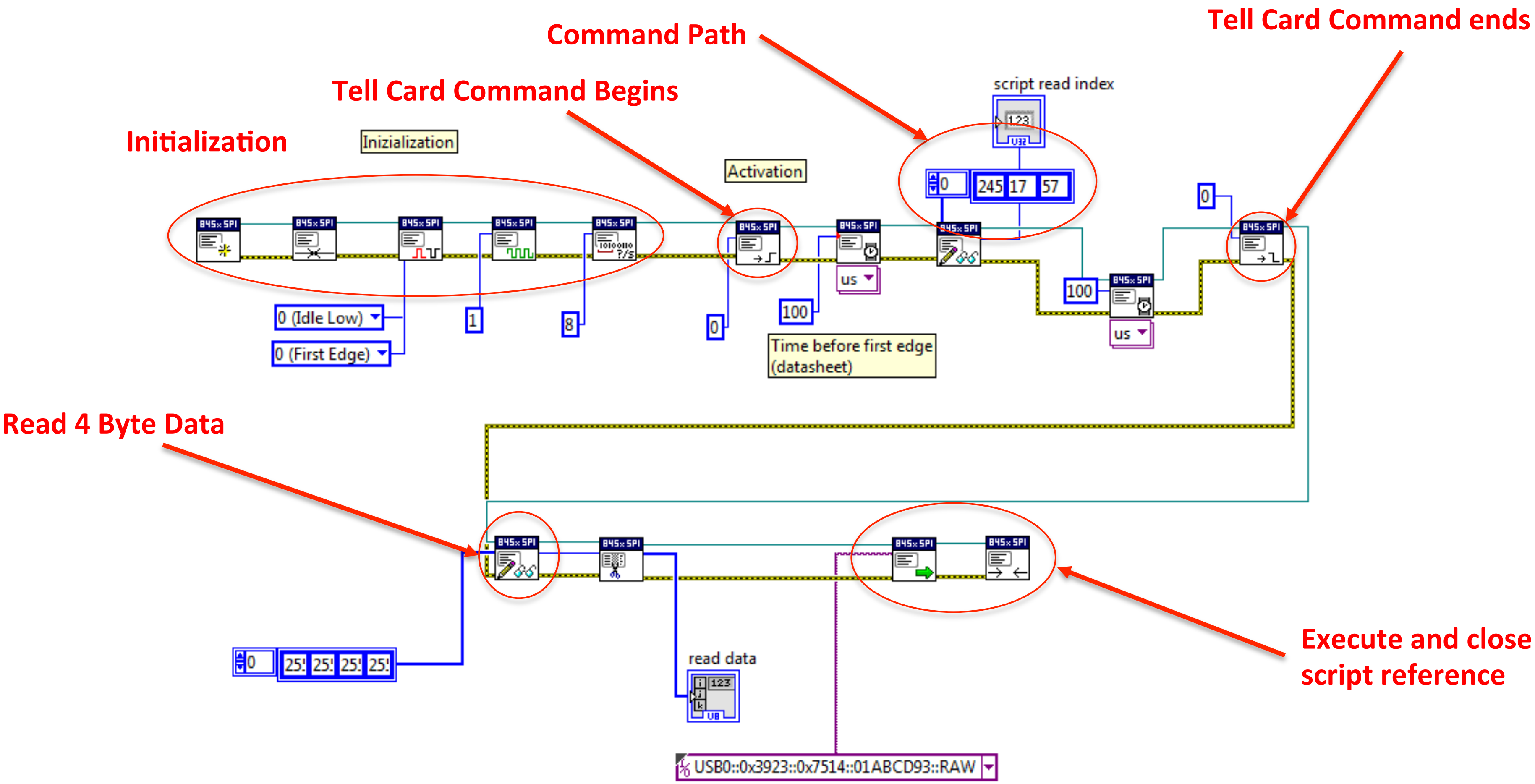


- Tried to interface a Nikhef 3D B-sensor to an National Instruments SPI interface
- Goal was to readout one using LabVIEW software
- Over the board: 3 Hall probe sensor, 3 ADC (one for each sensor) and a microcontroller
- Not a pure SPI protocol, needed a custom 3-4 byte command to begin the communication with each sensor



Nikhef 3D B-Sensor

3D Hall probe SPI interface: LabVIEW script



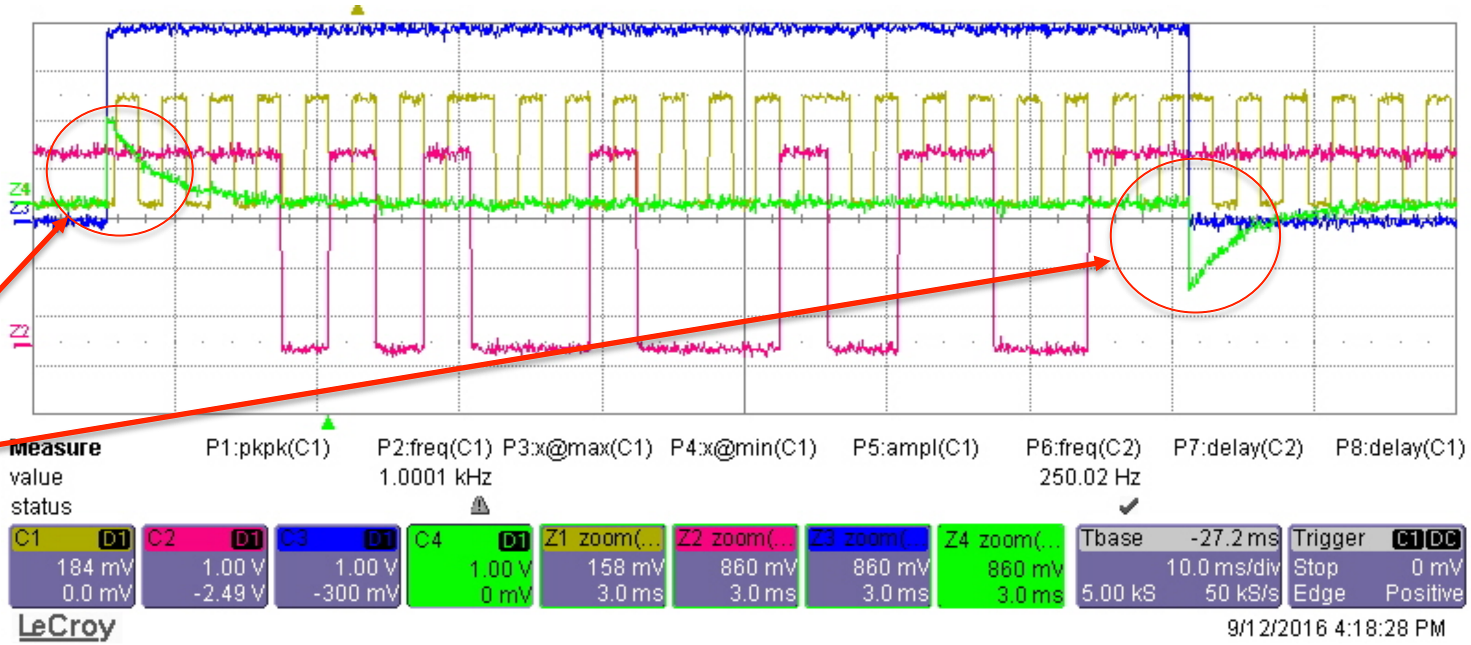
- Used LabVIEW SPI scripting to implement 3-4 bytes command path

3D Hall probe SPI interface: oscilloscope output

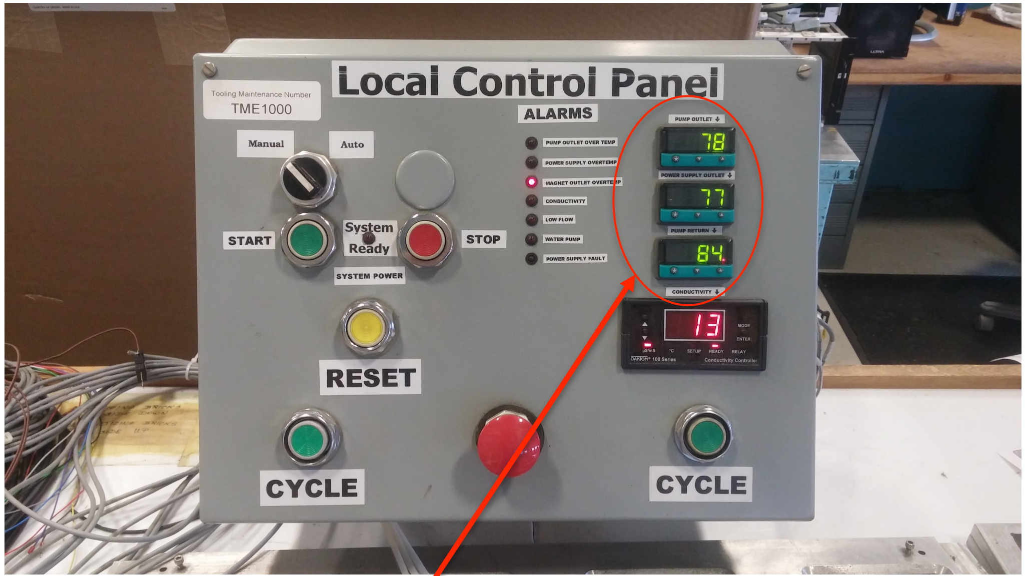
- Verified timing and output data using a LeCroy WaveRunner oscilloscope
- Tried to connect Hall probe => unclear response from the board
- No support from Nikhef, had to abort further efforts

Yellow: Clock
Red: MOSI Data
Blue: Chip Select
Green: SDO_ENA

Floating Line SDO_ENA



Instruments setup: control panel and NMR probe



Cooling water temperature panel

Metrolab Teslameter PT 2025 NMR probe

Water cooling temperature

- Configurable water cooling set-point (open to external heat exchanger circuit)

- Based on Nuclear Magnetic Resonance #4 Probe (0.4-1.05T), #5 Probe (1-2.1T)
- Error in absolute value in order of 10^{-6}
- Select probe dependent on field strength

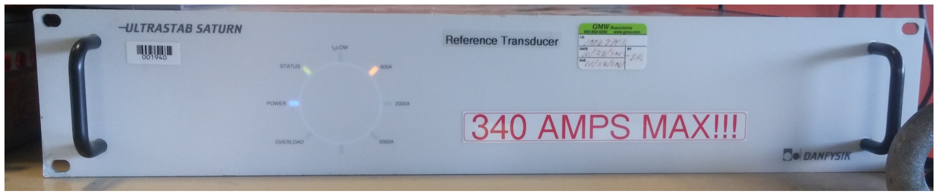
Instruments setup: digital multi meter - DMM

- Took temperature of coils, poles, NMR probe and yoke using an infrared sensor
- Used 2 DMM to monitor supply current and voltage (Keithley 2001 and HP 3457A)
- In order to have better resolution on current, used Agilent 3458A multimeter
- Danfysik Saturn transducer to stabilize current (also coil's current measurement)

Keithley 2001 DMM

HP 3457A DMM

Agilent 3458A Multimeter



Saturn Tansducer

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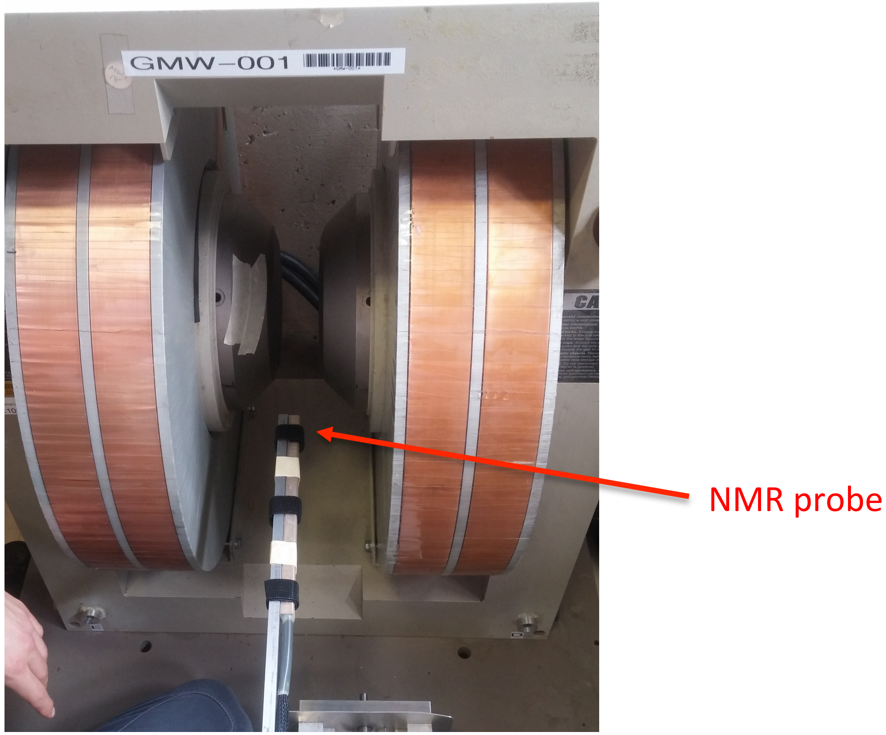
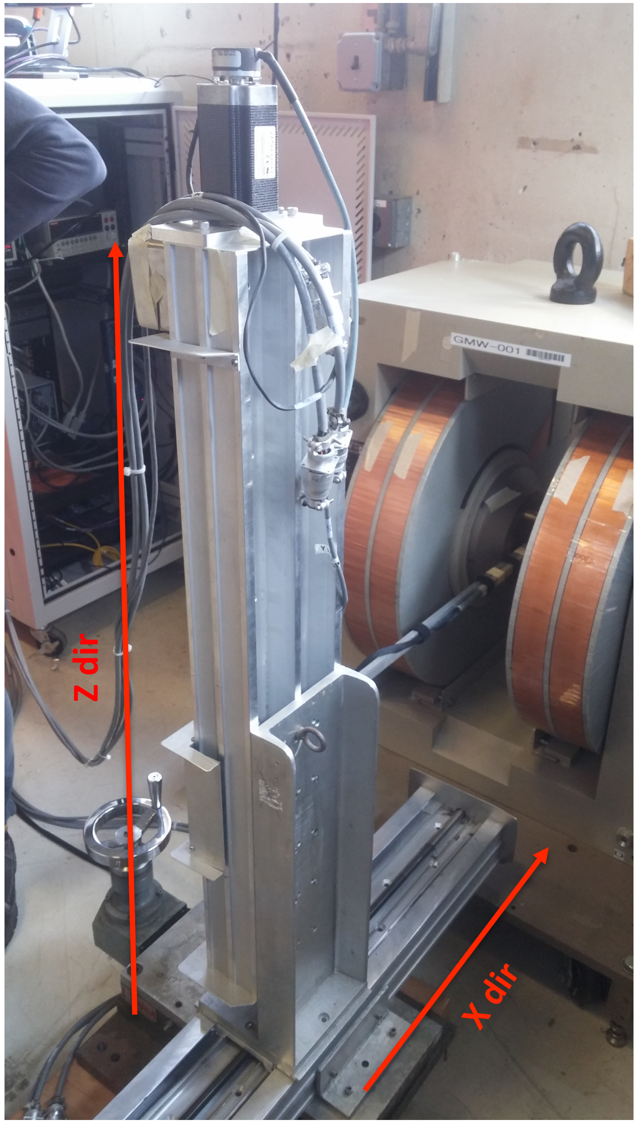
Magnet and robot setup

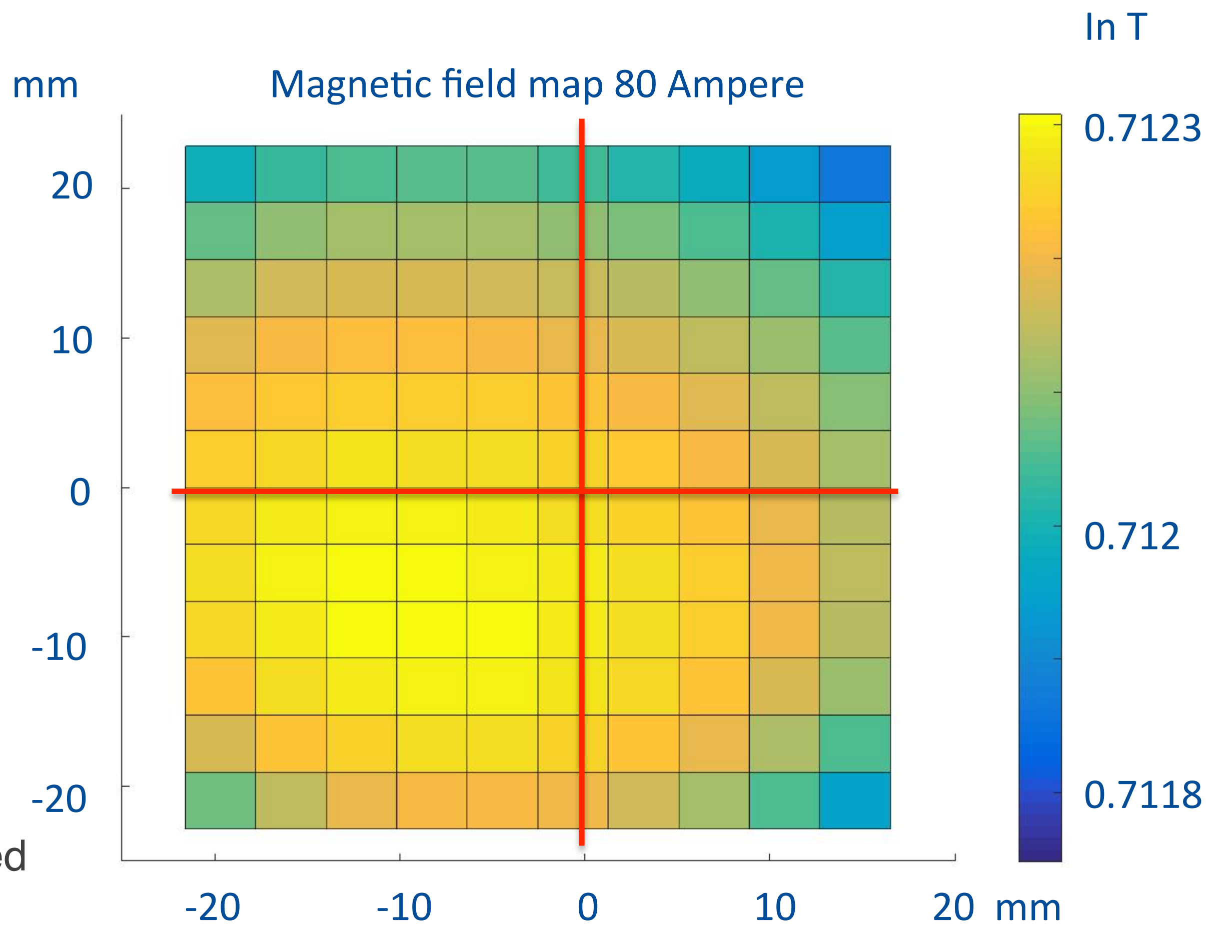




- Mapped magnetic field along parallel line, over x axis
- Obtained a mesh combining different lines at different z coordinate

First Map

- Coil's current 80 A
- Water cooling temperature set-point 85 F
- Used NMR N.4 (0.35 – 1.05 T)
- Position of the field peak not in center of the pole
- From simulation we can explain this with skewed poles
- Measured gap size and confirmed the skew (about 1mm)



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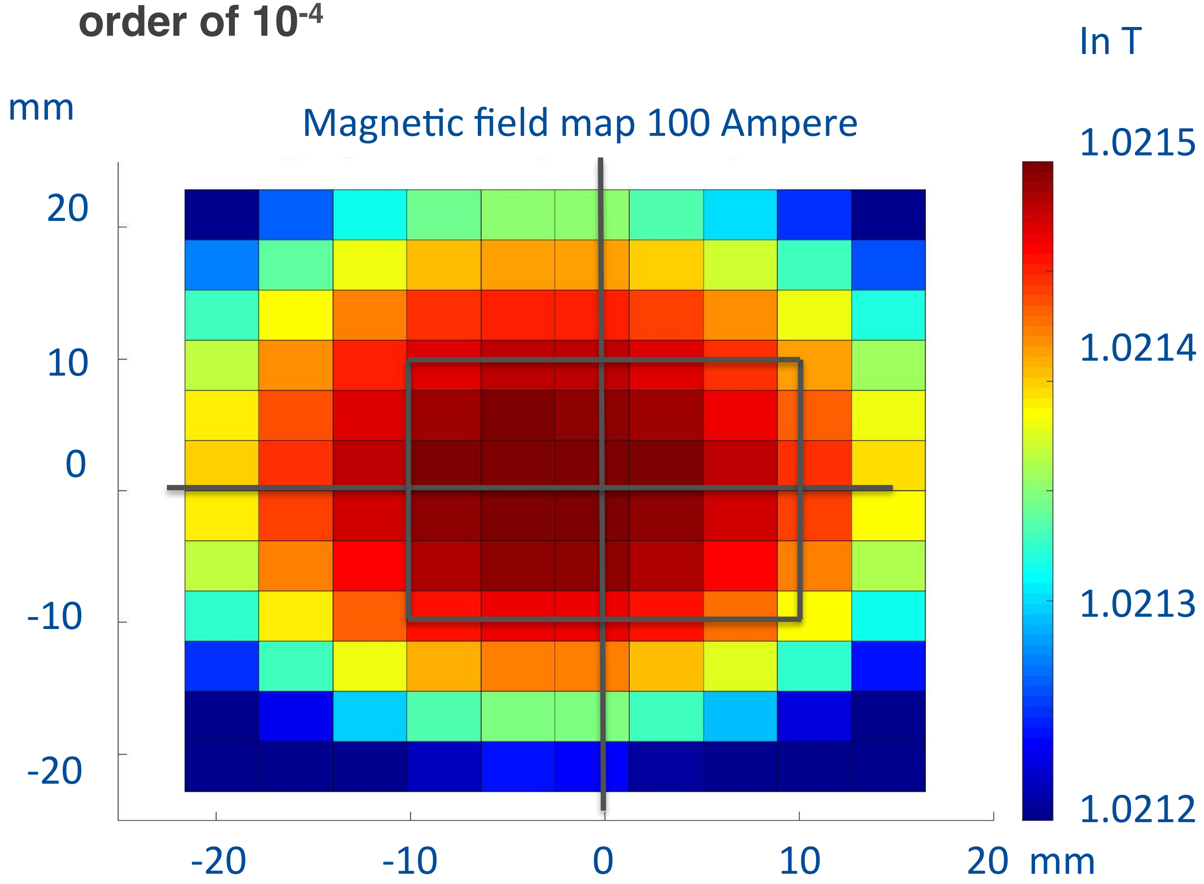
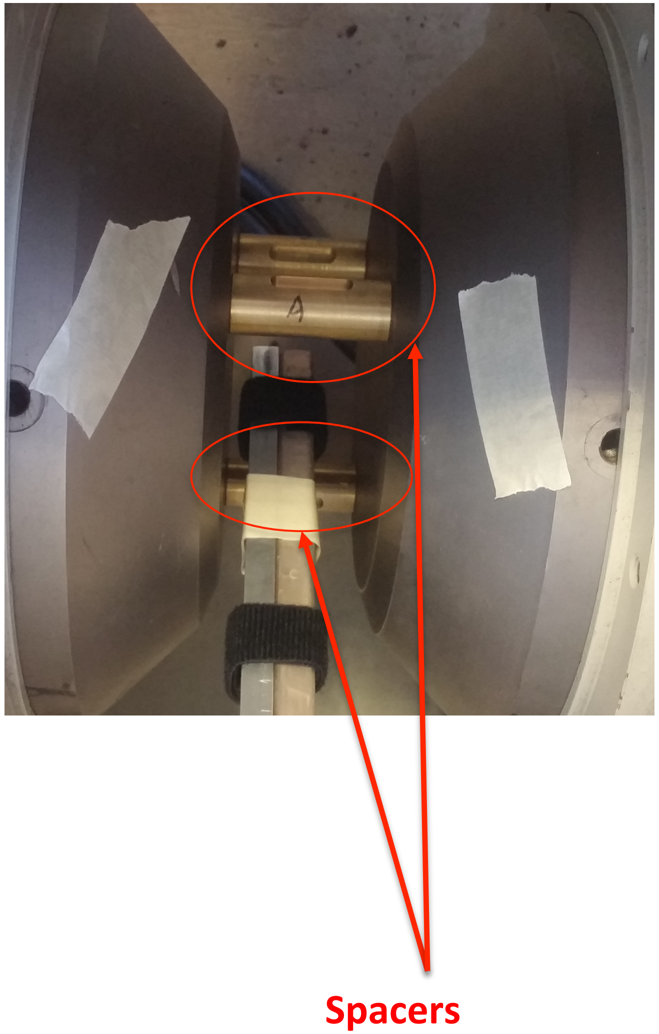
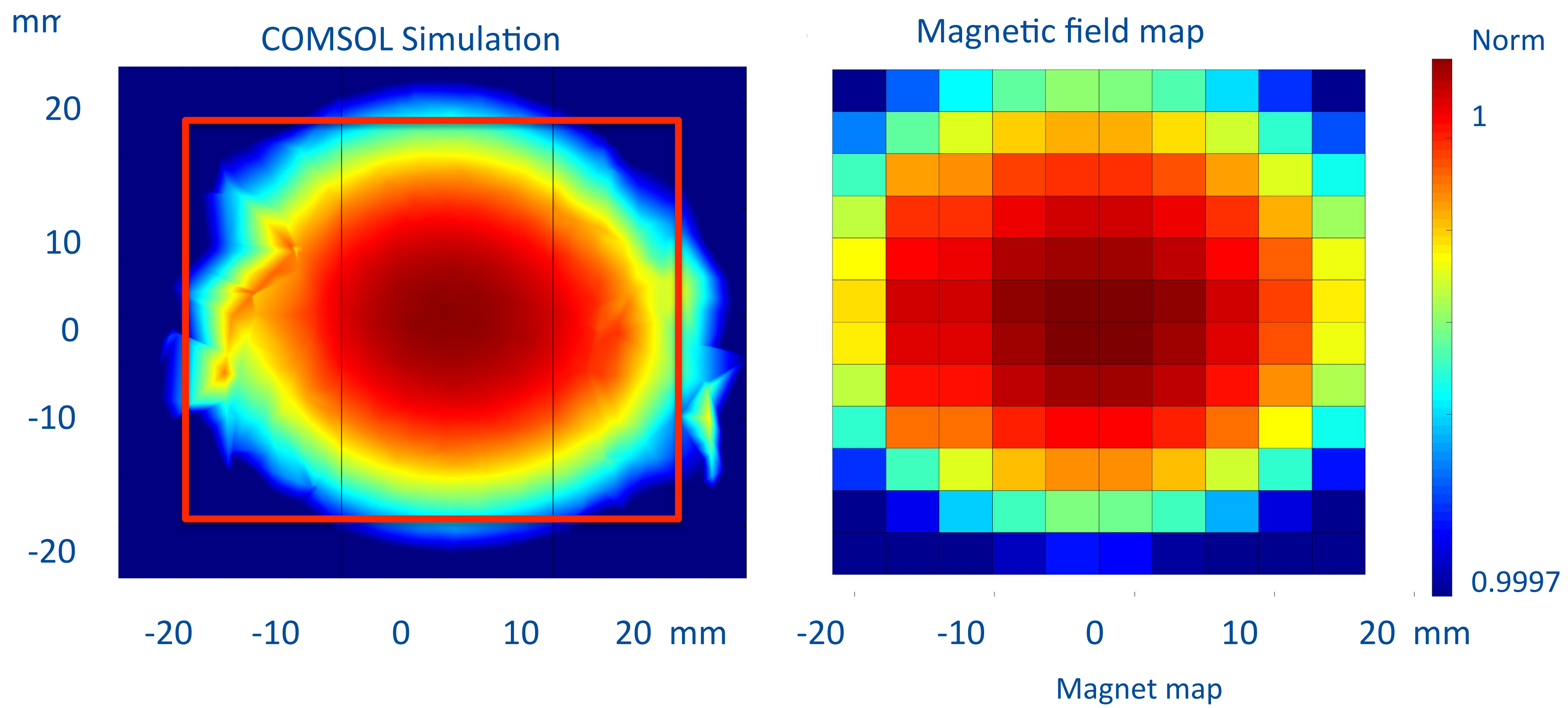
Skew correction

- Used 3 spacers to obtain parallel coils => mostly central peak
- **Spatial variations in region of interest (2cmX2cm) in order of 10^{-4}**





COMSOL vs Real magnet



- Shape of the field is very similar
- Normalized value (different current in simulation and mapping)

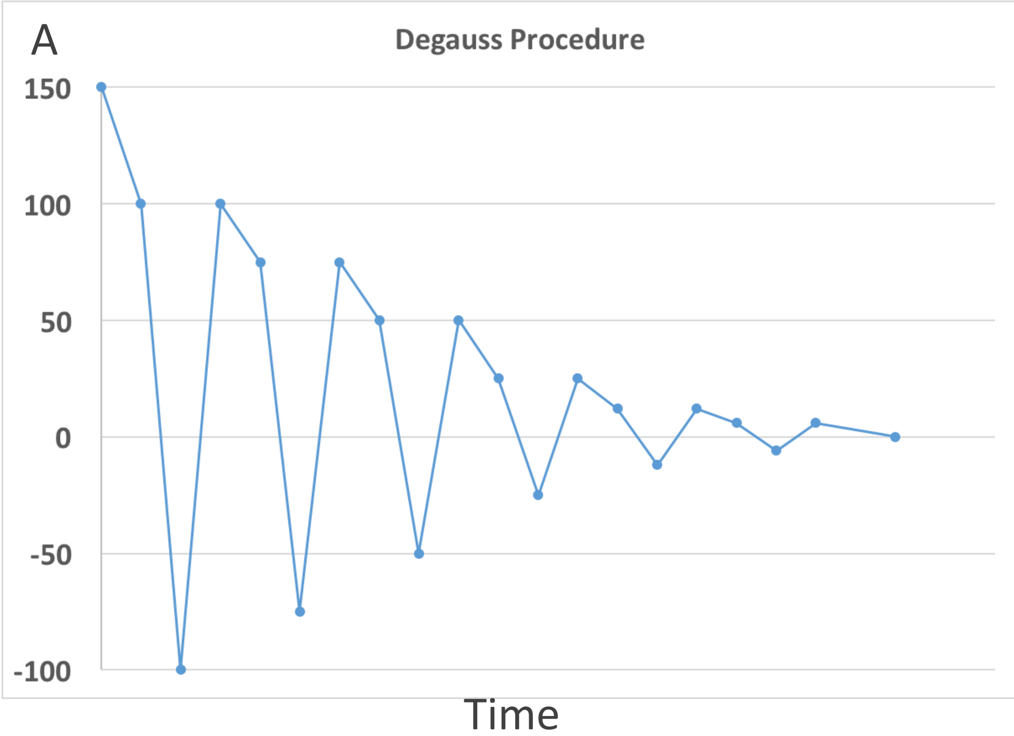
Challenges discovered during the mapping procedure

- Inconsistent data between two different maps (absolute value) yet magnet current appears stable
  - Increase Resolution on current reading, Keithley DMM reading has 10^{-4} error
  - Borrow an Agilent 3458A DMM => better resolution on current changes 10^{-6}
- Saw hysteresis effect
  - Order 10^{-2} change in the field between ramps
  - Introduced Degauss procedure to avoid it (see next slides)
  - Introduced a ramping profile to increase repeatability
- Still unstable measurement over time
  - Tried to change the cooling circuit temperature set point to study the effect (see next slides)

Degauss procedure/ Changing cooling circuit temperature setpoint

Degauss Procedure

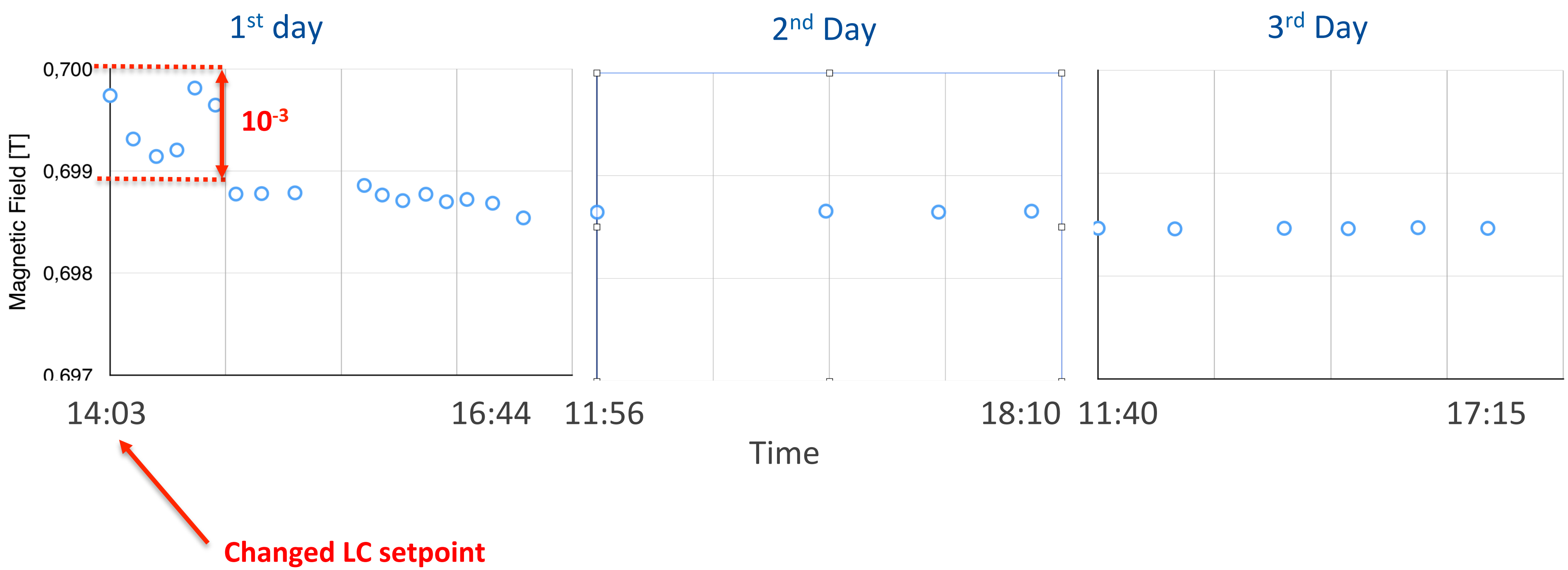
- Procedure used to avoid the memory effect of pole's previous magnetizations
- Set different positive and negative current to obtain the goal



Cooling circuit temperature set-point

- Cooling circuit set-point changed to 100 F
- Saw magnetic field reach a stable point after some hours

Final Results



- Monitored one point in the center of the magnet over time
- After introduced degauss procedure and increased the cooling circuit temperature, we reach better results, as we can see in the graph above
- Time variations of absolute value of the magnetic field of 10^{-4}

Conclusions

- Simulations on COMSOL are very helpful in understanding of the calibration magnet and field uniformity
- Field Map obtained shows the magnet has initial uniformity of <10^{-4} in center region (2cmx2cm) (region of interest)
- Saw unstable field over time, investigation shows that the power supply was not stable enough (10^{-3} shift over 4h)
  - Changing of cooling water temperature improves stability to 10^{-4}
  - Power supply needs to be stabilized further in order to improve stability over time
- We did not shim the magnet, as we investigated the source of the time variations in detail.

Summary

- Personally I learned
  - COMSOL magnetic field module
  - Operation and characterization of a real magnet, challenges in obtaining high homogeneity of the field
  - Teamwork
  - English in professional environment
  - Interaction with technicians, engineers and scientists was interesting and stimulating

- For my personal goal of the internship, I achieved:
  - Better understanding of challenges to face in experimental tasks
  - Improved my knowledge and skills
  - Learned about physics and experiments at Fermilab

Thank You!