MEG II実験
陽電子スペクトロメータの
3次元磁場測定

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Core-to-Core Program

MEG II
Mu - E - Gamma collaboration

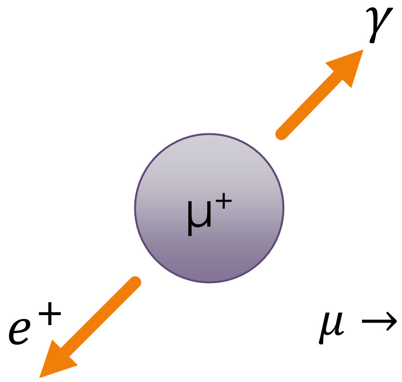
ICEPP
The University of Tokyo

MEG II experiment

- We search for cLFV decay, $\mu \rightarrow e\gamma$
- Aimed branching ratio sensitivity: 6×10^{-14} (90% C.L.)
  ⇔ Prediction from bSM (e.g. SUSY-seesaw): $O(10^{-12}\sim 10^{-14})$

Discovery of $\mu \rightarrow e\gamma$ = Discovery of new physics!

Key concepts of the experiment:
- High intensity μ^+ beam ($7 \times 10^7 \mu$/s) @ PSI
- **High resolution detectors** to distinguish signal from accidental BG



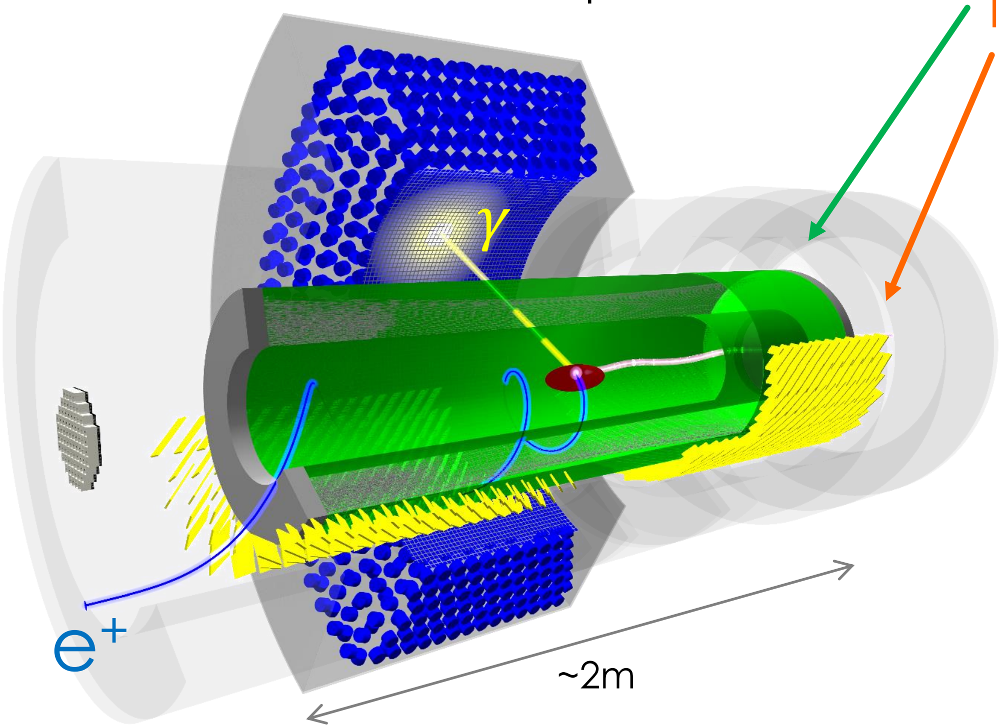
$\mu \rightarrow e\gamma$ signal

$E_e = E_\gamma = 52.8$ MeV
back-to-back
same timing

e^+ spectrometer and COBRA magnet

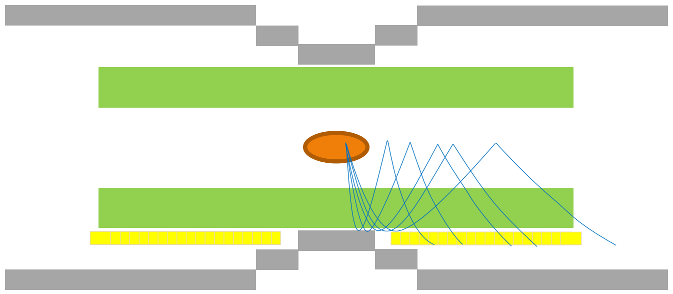
e^+ spectrometer = Drift chamber / Timing counter + **COBRA magnet**

(reused from MEG)

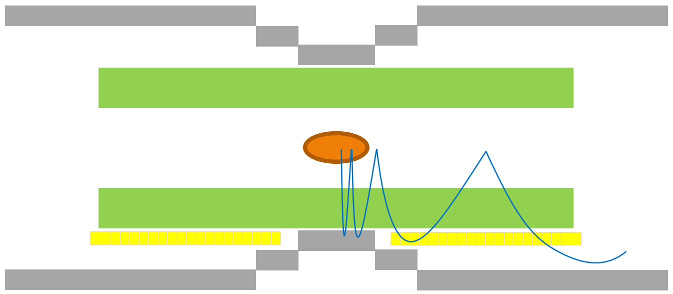


COnstant Bending RAdius magnet
- Superconducting magnet, ~1.2 T at center
- **Gradient field**

Same radius at different angles for same p_{e+}



e^+ is swiped away quickly
→ hit rate reduces



Requirement for B-field measurement

Resolution will improve in MEG II:

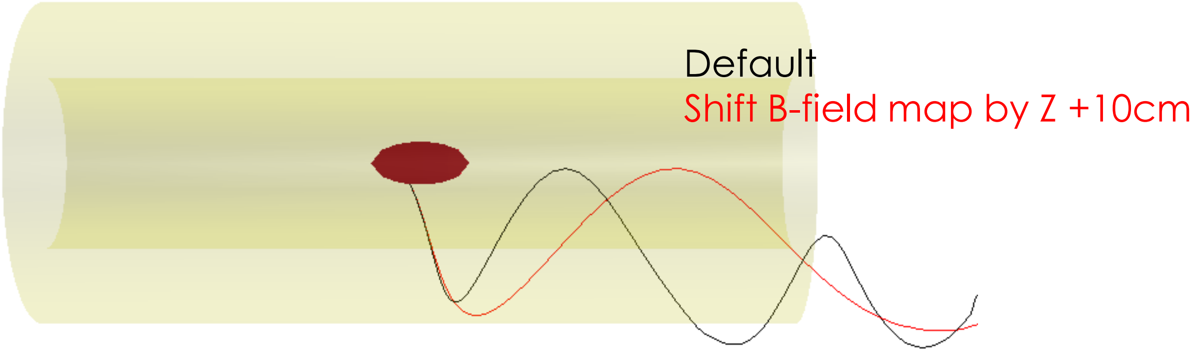
$\Delta p_e \sim 83$ keV (0.16%, was 0.7% in MEG), $\Delta z_e \sim 1.6$ mm, $\Delta y_e \sim 0.7$ mm

→ **B-field uncertainty should be <~0.1%**

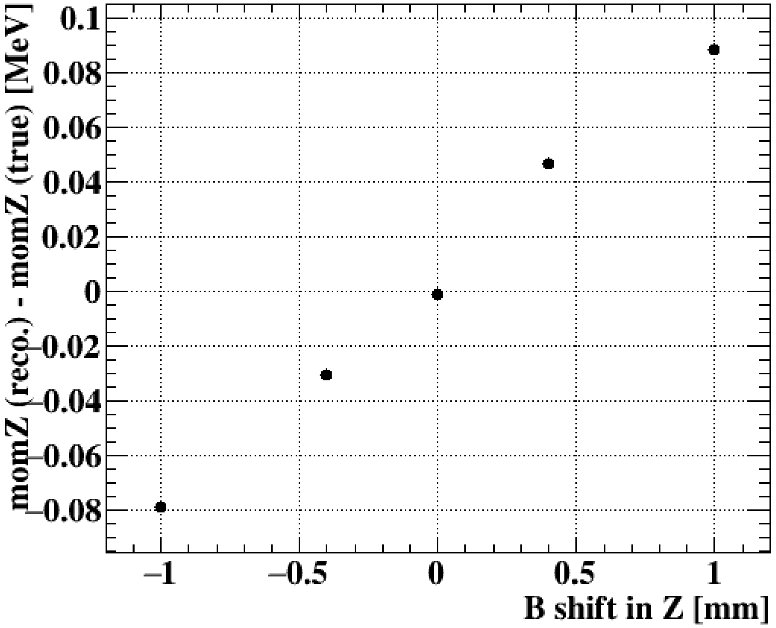
Alignment of the sensor is important

→ e.g. If B-field map is shifted in Z by 0.5 mm,
p_z is biased by ~40 keV, vertex Z is biased ~0.2 mm

Example of signal positron track



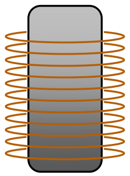
Bias in p_z vs. shift of B-map in Z



Difficulties in gradient B-field measurement

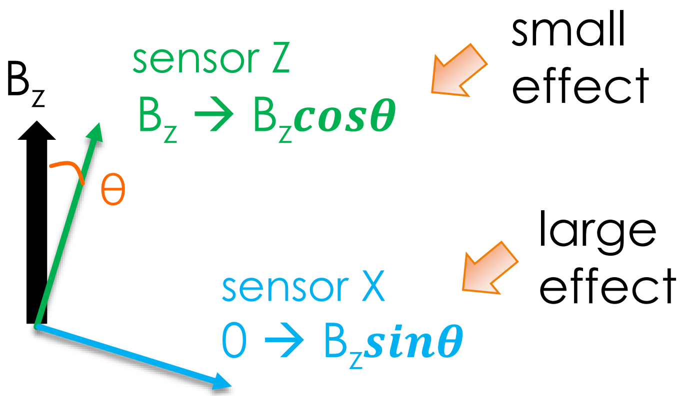
Gradient B-field
→ Strength and direction of the B-field changes at different place.

- Sensor position must be known well
  - Position shift will make a bias in e^+ reconstruction.
  - Some commercial sensors are too large



e.g.
NMR probe is usually too big

- Measure the field in 3 directions.
  → Angle misalignment makes a large effect

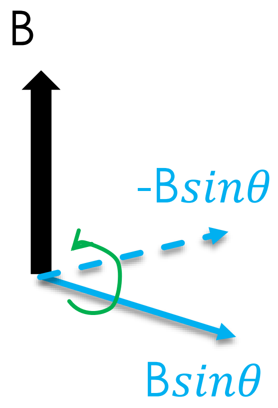


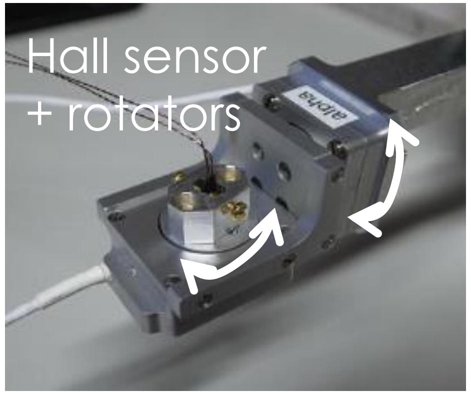
Previous measurements (for MEG)

A. **Commercial 3D** Hall sensor + moving wagon
Angle error was large (9 mrad)
→ Only B_Z was used. B_R and B_Φ were calculated from Maxwell equations.

B. **1D** Hall sensor + **rotating stage** + moving arms
→ **Cancel out the effect of misalignment** by rotating sensor.
→ Data taking time was long (~1 week).
It was also necessary to consider the misalignment of the rotating stage

Difference between measured and calculated field was ~0.2% (in RMS)



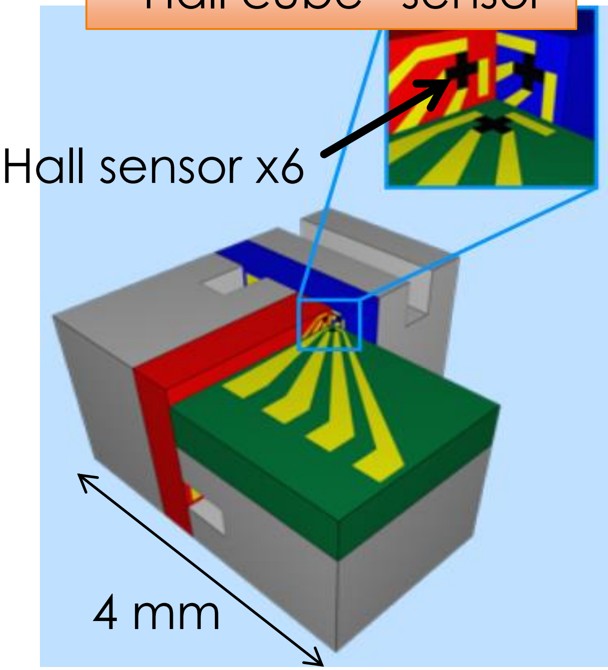


Improvements in new measurement

- Use **“Hall cube” sensor** developed at PSI.
  - 6 Hall sensors to measure 3 directions (2 sensors for each direction)
  - Sensors are mounted in a **small** space (200 μm).
  - Cuboid structure makes the sensor **orthogonal** to each other.

- Use a **coordinate finding magnet** to measure the sensor directions.
  It consists of Nd magnets which provide uniform field with known direction.

“Hall cube” sensor



Coordinate finding magnet

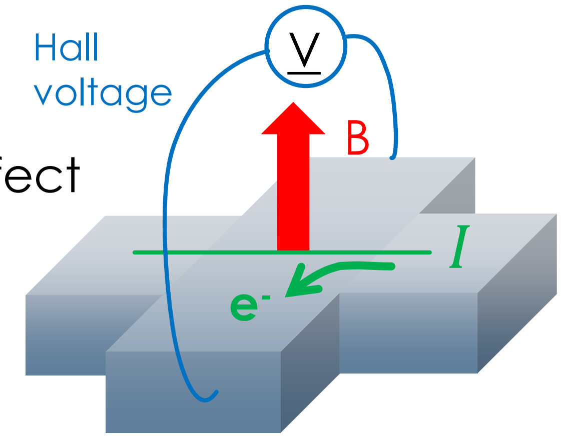
Hall sensor

- Hall sensor
  - Simple, easy to use
  - Careful calibration is required (small non-linearity exists)
  - Gain drift (by temperature etc.)
    → monitoring
  - Planar Hall Effect (<0.2%)
    → cancel out by having two sensors in each direction with 90 deg. rotated.

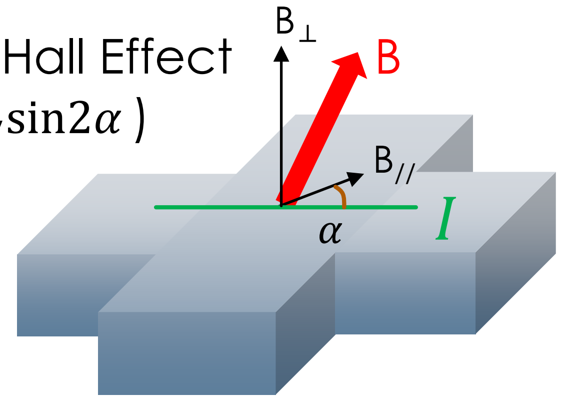
Minor issues with our sensor:

- Instability of one of our sensor was relatively large (<0.1%)
- We broke one out of 6 sensor by accident. Fortunately, PHE for that sensor (Z) is expected to be negligible.

Hall effect



Planar Hall Effect
($\propto IB_{//}^2 \sin 2\alpha$)



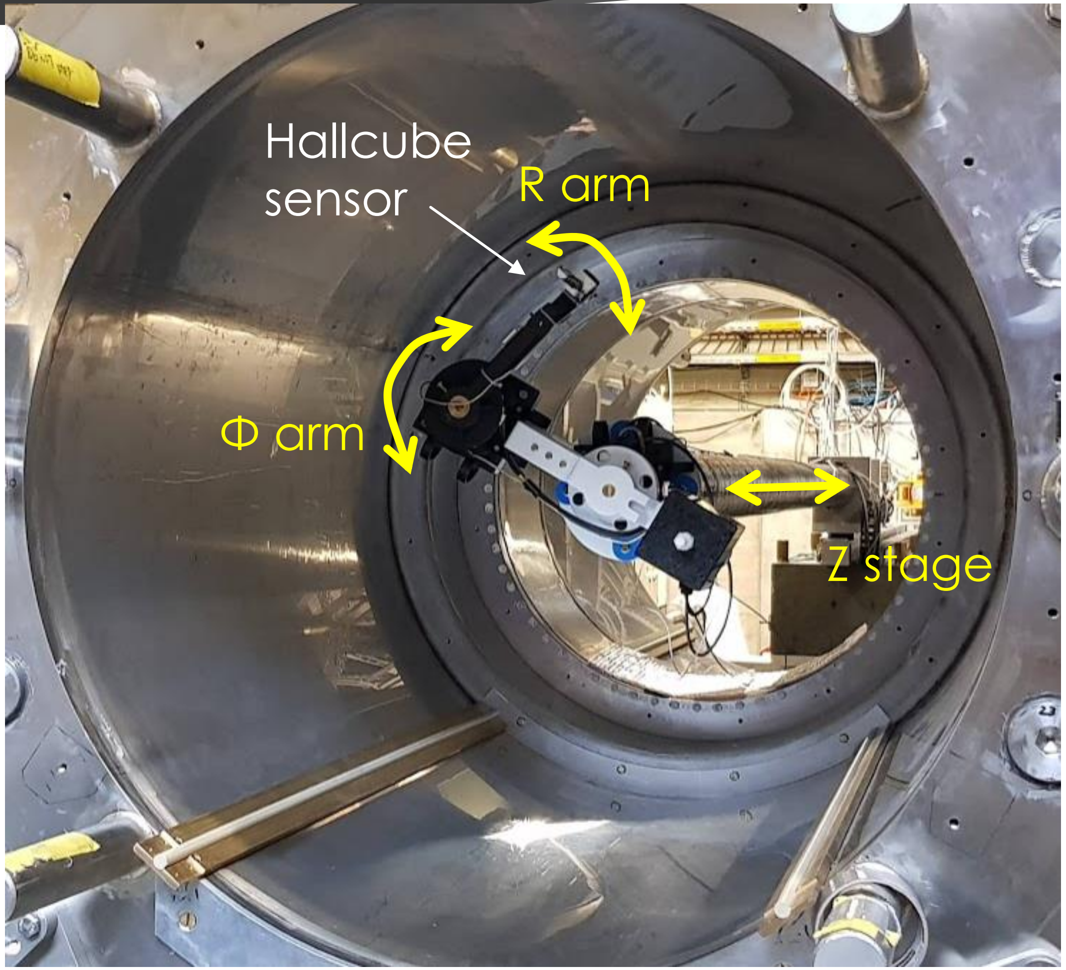
Measurement system

- Two moving arms + encoders
  Supersonic motors (works in B-field)
  + 3D printed arms (reinforced w/ CFRP)

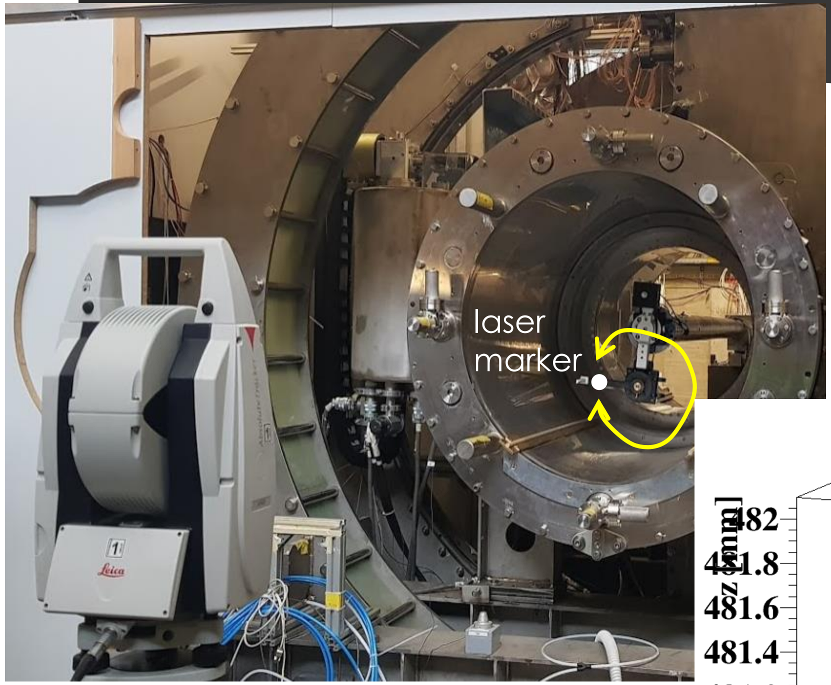
- Z stage + encoder
  ~3m long, toothed belt
  Granite table (stable) + CFRP tube (light)

- Sensor
  Hallcube + current source (Keythley 6221)
  + Digital voltmeter (Agilent)

- Control system
  EPICS (multiple devices, real time)

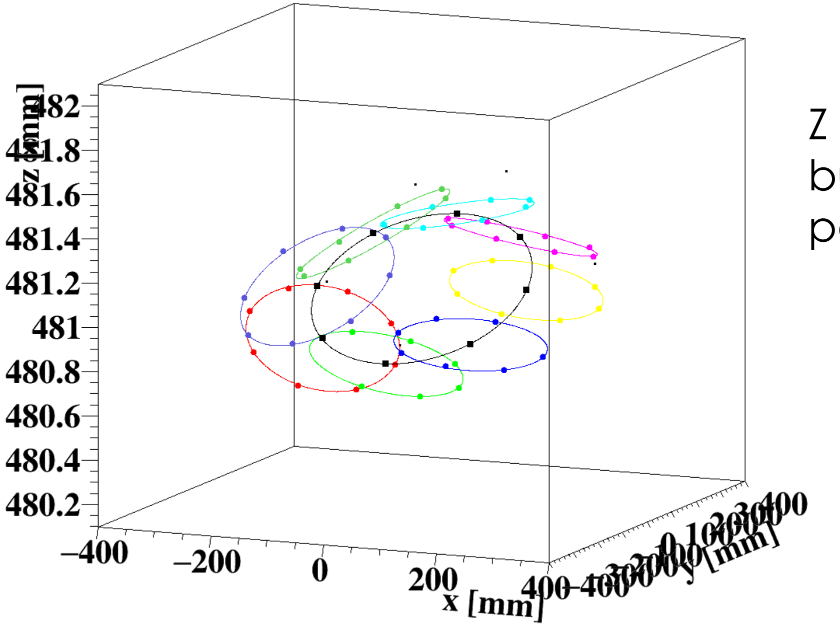


Survey of the mapping machine



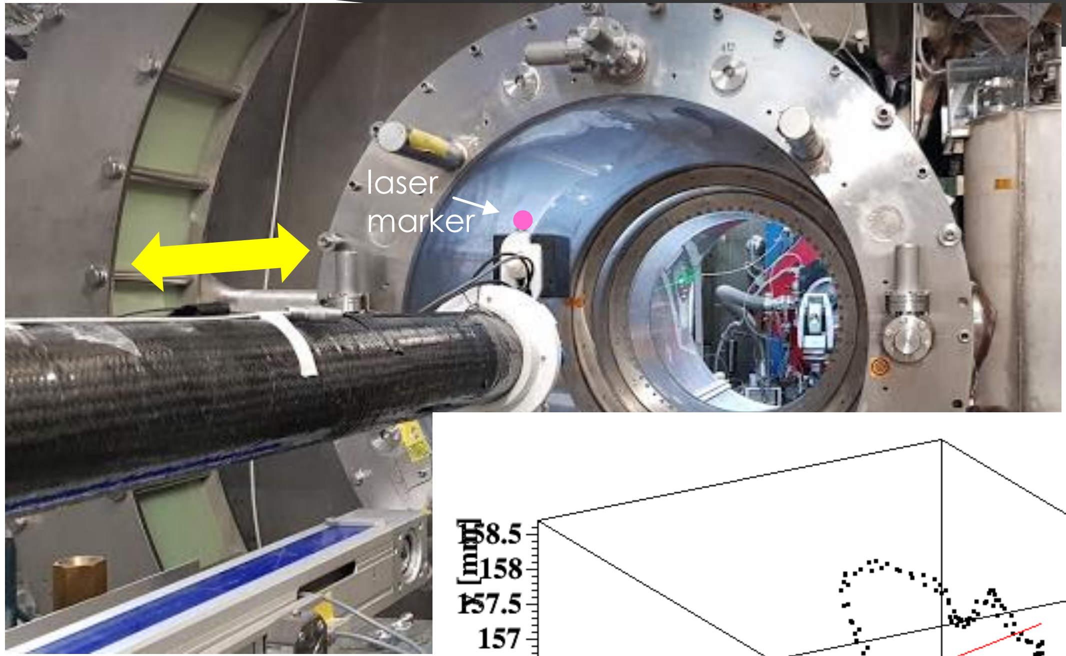
Position and tilt of the arms are measured in laser survey.

Colored circles: R arm rotation
Black circle: Phi arm rotation (center of R circles)



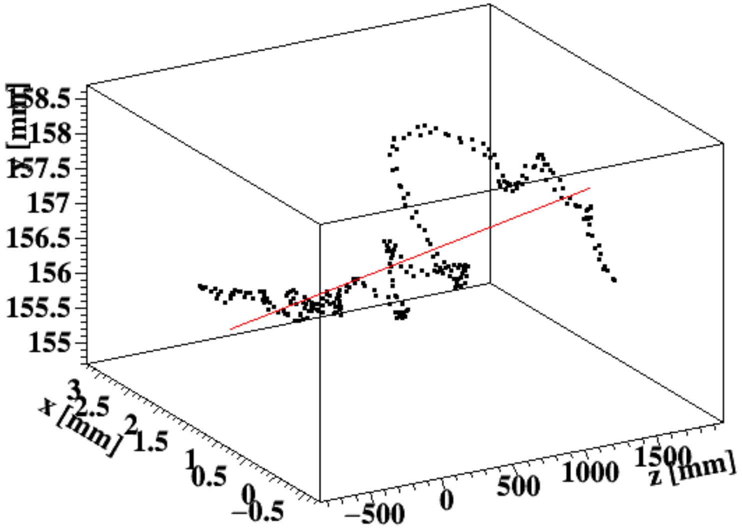
Z position is found to vary by ~0.5mm due to tilt, but we can correct this based on the tilt parameters obtained in this survey.

Survey of the mapping machine



Linearity of the stage is also measured and corrected.

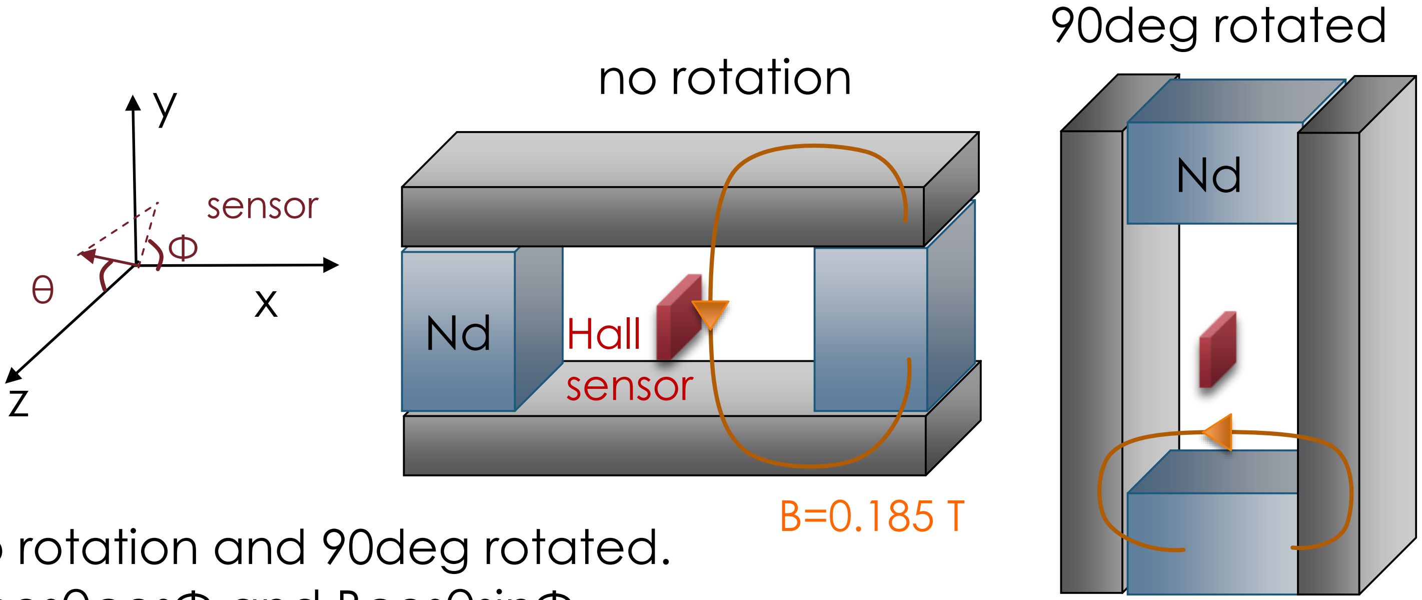
Deviation in XY was ~1.5 mm at maximum.



After the corrections of tilt and Z linearity, deviation (RMS) of surveyed X,Y,Z positions from calculated position were **~200 μm in X,Y, ~30 μm in Z.**

Sensor direction measurement

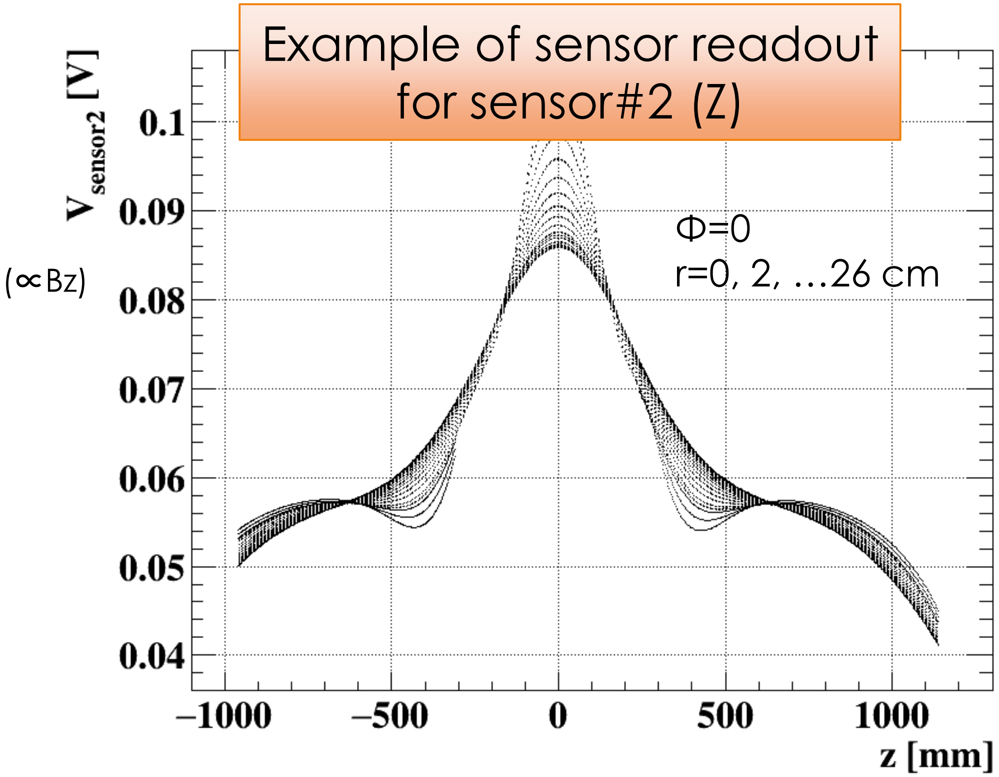
Sensor direction was measured by using Nd magnets which provides uniform field with known direction.

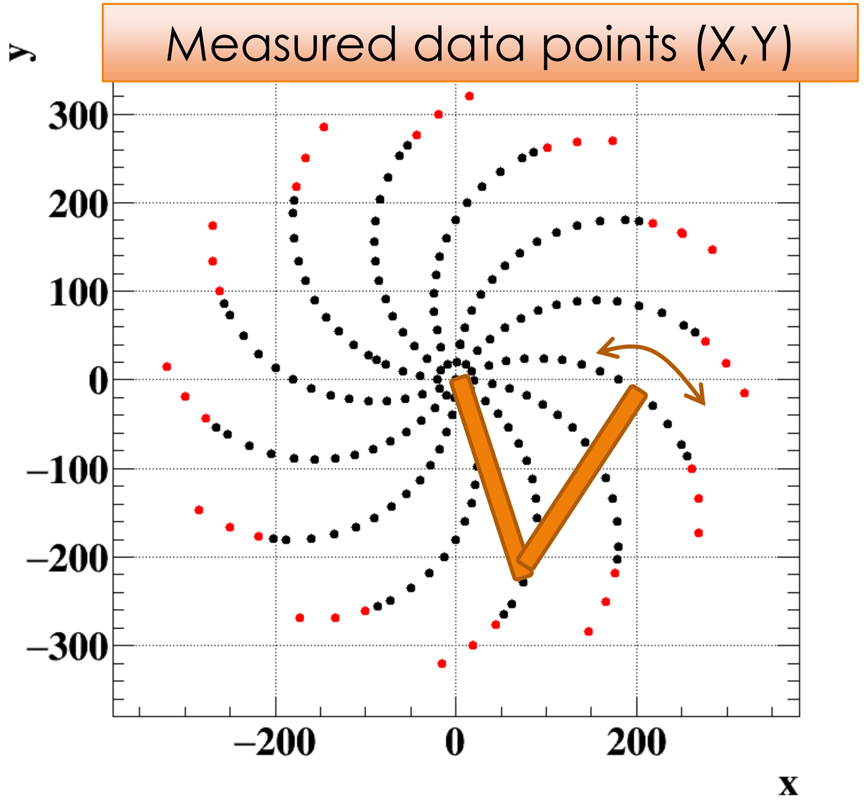


We measured the B-field with no rotation and 90deg rotated.
Measured field correspond to BcosθcosΦ and BcosθsinΦ.
→ θ and Φ are calculated.

Data taking

We did a full mapping in 1 day (very quick!).
30deg step in ϕ, 2 cm (or 1 cm) step in R, ~5 mm step in Z

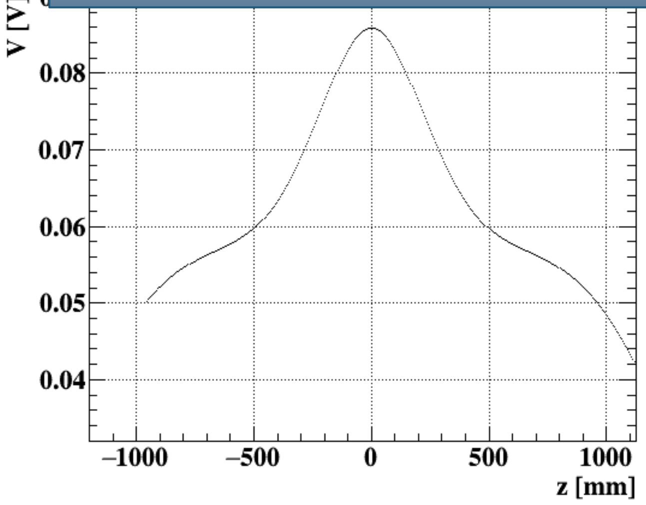




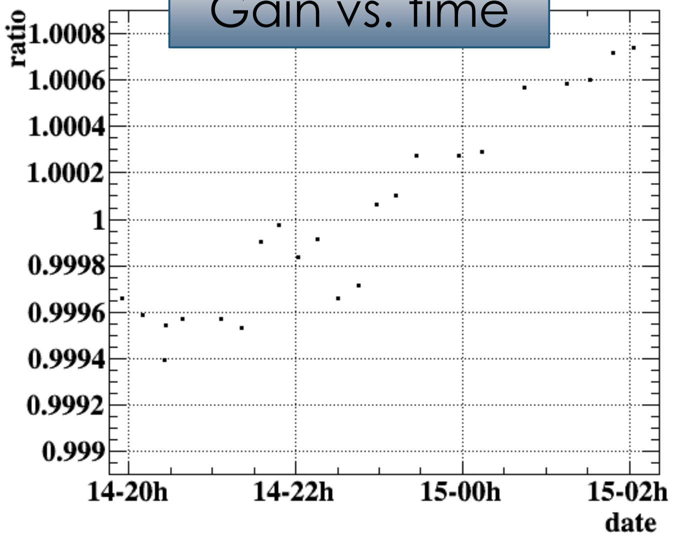
Stability check

Gain of Hall sensor may vary due to temperature etc.
We monitored the gain and offset by scanning over Z every 10 min. at COBRA center.
Variation of offset was negligible. Gain change of ~0.1% will be corrected.

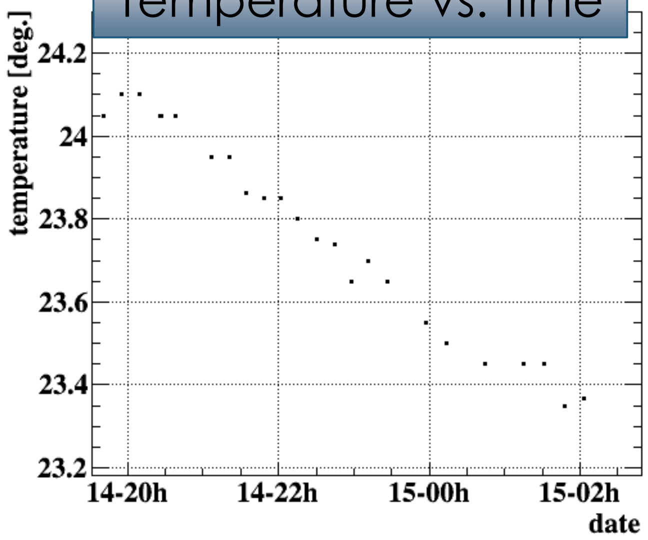
Example of monitoring data



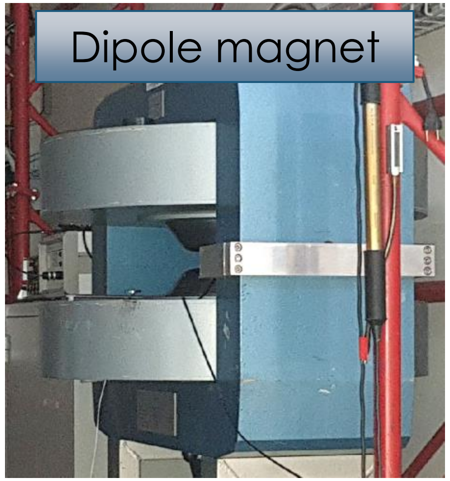
Gain vs. time



Temperature vs. time



Next steps



- Calibration (V→Gauss) of Hall sensor
  Using dipole magnet + NMR probe (reference)

- Interpolate discrete points to make full 3D map
  Previous method:
    B-spline (2D spline) fit in each R-Z planes at different φ
  New method:
    Fit with solutions to Maxwell equations for generic solenoid

    $B_Z = \sum_{n,m}(C_n \cos(n\phi) + D_n \sin(n\phi))\, k_m I_n(k_m r)(-A_{nm} \sin(k_m z) + B_{nm} \cos(k_m z))$ etc.

    Fitting software used in Mu2e is adopted for MEG.
    Misalignment of the sensors can be included in the fit parameters.

Summary

- High precision (~0.1%) is required for the measurement of the gradient B-field of MEG II COBRA magnet.

- We successfully performed mapping:
  - 3D "Hallcube" developed at PSI + moving system were used.
  - Moving stage was carefully surveyed with good precision (e.g. ΔZ~30 μm).
  - Direction of the sensor was measured by dedicated setup with permanent magnet.
  - Stability (gain variation of <0.1%) of the sensor was monitored every ~10 min.

- Calibration of the sensor and interpolation of the data points will be done to make a final B-field map for MEG II.