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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MEG II experiment

- We search for cLFV decay, $\mu \rightarrow e\gamma$
- Aimed branching ratio sensitivity: $6 \times 10^{-14}$ (90% C.L.)
  $\Leftrightarrow$ 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 $\mu^+$ beam ($7 \times 10^7 \mu/s$) @ PSI
- High resolution detectors to distinguish signal from accidental BG

$E_e = E_\gamma = 52.8$ MeV
back-to-back
same timing
e⁺ spectrometer and COBRA magnet

Drift chamber + COBRA magnet

( reused from MEG)

COnstant Bending RA dius 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:
\[ \Delta p_e \sim 83 \text{ keV} \ (0.16\%, \text{ was } 0.7\% \text{ in MEG}), \ \Delta z_e \sim 1.6 \text{ mm}, \ \Delta y_e \sim 0.7 \text{ mm} \]

\[ \Rightarrow \ B\text{-field uncertainty should be } \sim 0.1\% \]

Alignment of the sensor is important
\[ \Rightarrow \ e.g. \text{ If B-field map is shifted in } Z \text{ by } 0.5 \text{ mm}, \]

\[ p_z \text{ is biased by } \sim 40 \text{ keV}, \text{ vertex } Z \text{ is biased } \sim 0.2 \text{ mm} \]

Example of signal positron track

### Bias in \( p_z \) vs. shift of B-map in Z

![Graph showing bias in \( p_z \) vs. B shift in Z](image-url)
Difficulties in gradient B-field measurement

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

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

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

e.g. NMR probe is usually too big

\[ B_z \rightarrow B_z \cos \theta \] small effect

\[ 0 \rightarrow B_z \sin \theta \] 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 $B_\Phi$ 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)
• 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 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.

Planar Hall Effect ($\propto IB_\parallel^2 \sin 2\alpha$)
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.
Linearity of the stage is also measured and corrected. Deviation in XY was \(\sim 1.5\) mm at maximum. After the corrections of tilt and Z linearity, deviation (RMS) of surveyed X,Y,Z positions from calculated position were \(\sim 200\ \mu m\) in X,Y, \(\sim 30\ \mu m\) in Z.
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 $B\cos\theta\cos\Phi$ and $B\cos\theta\sin\Phi$.

$\Rightarrow \theta$ and $\Phi$ are calculated.
We did a full mapping in 1 day (very quick!).
30deg step in $\phi$, 2 cm (or 1 cm) step in R, ~5 mm step in Z

Example of sensor readout for sensor#2 (Z)

Measured data points (X,Y)
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.
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.
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.