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Magnetic Field Measurement & Analysis of the Detector Solenoid for COMET Experiment

Shohta Takami[1], Masaharu Aoki[1], Ryo Nagai[1], Ohhata Hirokatsu[2], Masami Iio[2], Ken-ichi Sasaki[2], Naoyuki Sumi[2], Makoto Yoshida[2]

[1]*The University of Osaka*, [2]*High Energy Accelerator Research Organization*

✉ : s-takami@epp.phys.sci.osaka-u.ac.jp

1. Introduction

COMET Experiment

New physics need to be observed for advancing Standard Model of particle physics.

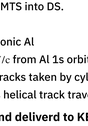
COMET aims to search new physics called μ-e conversion.

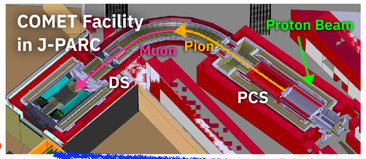
Normal Decay of Muon : $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ → Back Ground

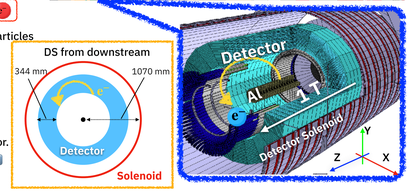
μ-e conversion : $\mu^- N \rightarrow e^- N$ → Signal for COMET

COMET beamline consists of solenoid magnets.

- Pion Capture Solenoid (PCS)
  - excellent acceptance for pion capture
- Muon Transport Solenoid (MTS)
  - Curved 3 T solenoid & 0.04 T dipole field filter positive/ high momentum particles
- Bridge Solenoid (BS)
  - Connect smoothly the magnetic flux from MTS into DS.
- Detector Solenoid (DS)
  - Muons are stopped at Al target & form muonic Al
  - Signal electrons have momentum 105 MeV/c from Al 1s orbit
  - Momentum is calculated from electron's tracks taken by cylindrical detector.
  - DS's field strength is 1 T so that electron's helical track traverse detector







Our DS has beem fabricated by TOSHIBA and deliverd to KEK[2].

We performed commissioning test and magnetic field measurement to see the integrity of DS.

2. Detector Solenoid (DS)

DS is superconducting magnet and consists of 14 coils.

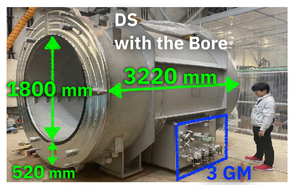
Cooling system is **3 GM cryocoolers** and **precooling pipe for Liquid N_2**

Coil Parameters

Material	NbTi/Cu
ratio(NbTi : Cu)	$1 : 4.2 \pm 0.5$
Wire Diameter	1.2 mm
material length	7 km
layer	7
turns/layer	135
RRR	184
length	170 mm
radius	1.07 m

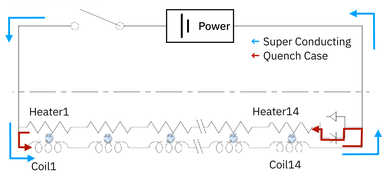
DS Parameters

The number of coils	14
Current	189 A
Mag Filed w/ iron yoke	1.0 T
Inductance	236 H
Stored Energy	4.2 MJ
Total material length	98 km



Horizonal Position accuracy of Coils in DS 's bore is ±1 mm.
Vertical Position accuracy of Coils in DS 's bore is ±1.6 mm.

Protection Circuit

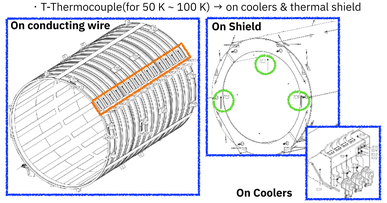


- Power is shut down as quench is detected.
- To prevent localized energy loss on a coil, diode switch current loop to **Red one.**
- Heaters warm up all coils and allows stored energy dissipate safely.
- On quench simulation, coils are all kept under 150K.

Temperature sensors

2 types of sensors

- Cernox (for cryogenic temp) → on conducting wires
- T-Thermocouple(for 50 K ~ 100 K) → on coolers & thermal shield



3. Commissioning Test without Iron yoke

Commissioning tests were done at TOSHIBA factory to check

- sufficient cooling for superconductivity
- excitation to rated current
- Coils's Temperature when shutted down

✅ Test1 Cooling Test

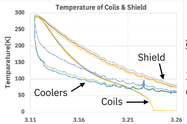
To keep superconductivity with the rated current 189 A , all coils should be cooled to 4.2 K.

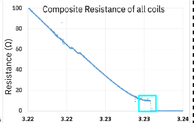
- **Cooling Scheme (2 weeks in Total)**

1st week : 3 GM coolers & Precooling by Liquid N_2→ 80 K

If without Precooling by Liquid N_2 took 5 weeks

2nd week : Only 3 GM coolers → 4.2 K





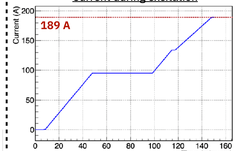
Suffciently cooled to 4.2 K.

Checked Super Conductivity.
Measured RRR : 185 (same as designed value)

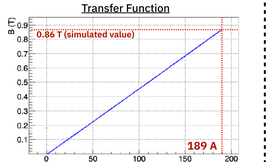
✅ Test2 Excitation Test

With the rated current, DS produces 1 T magnetic flux dencity at the center of the magnet.
We fixed 3-axis hall sensor at the center of DS and monitor magnetic field during excitation.

Current during excitation



Transfer Function



Successfully excited to **rated current 189 A without any training.**

Checked linearly excited to **simulated(w/o Iron yoke) megnetic flux density**

✅ Test3 Shut-Down Test

We shut down the power at several current manually, and see temperature of coils.

Peak Temperature after shut-down

Current	10A	95A	134A	189A
Peak temp	**5.7K**	**37.9K**	**46.9K**	**59.1K**

Checked peak temperatures are all under quench simulation 150 K

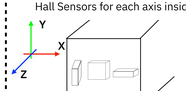
4. Magnetic Field Measurement(MFM)

This measurement aims to check integrity of coils inside cryostat.

Instrument

- Hall Probe
  HGM-8900A-R-5 V(ADS)

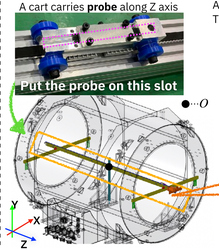
Hall Sensors for each axis inside



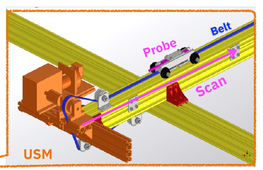
Each feels nominal magnetic flux.

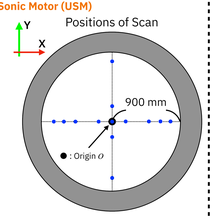
Method

A cart carries **probe** along Z axis



Align manually the frame at each axis to scan
The cart is connected to **belt** which is driven by **Ultra Sonic Motor (USM)**

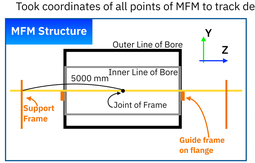


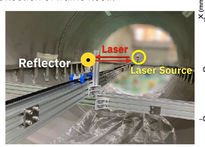


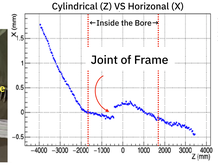
- Measure mag field 35 mm interval
- 10 times at each point to calculate σ_B

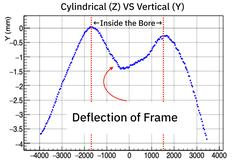
Coordinate Taking by Laser Tracker

Took coordinates of all points of MFM to track deflection of frame itself.









5. Analysis & Results

Sensor Calibration

Sensors are inclined to orthonormal system due to

- their mounting angles (~ 0.01 rad)
- deflection of frame (~ 0.001 rad)

This leads magnetic flux to project to others

- Angle Correction

If you have True vector of magnetic field,
you can correct it to the one in a inclined system.
Multiply from the left by inversed correcting matrix M
Measured magnetic vectors $\vec{B}^{meas}$ are in the inclined system,
so correct them in orthogonal system $\vec{B}^{orthogonal}$

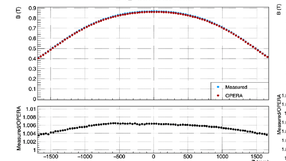
$$B^{inclined} \xrightarrow{M\left(\vec{n_x}\right)\left(\vec{n_y}\right)\left(\vec{n_z}\right)} \begin{pmatrix} B_x^{True} \\ B_y^{True} \\ B_z^{True} \end{pmatrix} \qquad B^{orthogonal} = \begin{pmatrix} \vec{n_x} \\ \vec{n_y} \\ \vec{n_z} \end{pmatrix}^{-1} \begin{pmatrix} B_x^{meas} \\ B_y^{meas} \\ B_z^{meas} \end{pmatrix}$$

$\vec{n_i}$: inclined normal vectors

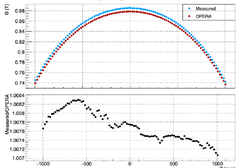
Sensor Calibration Result

After Correction, compare magnetic field distribution with simulation done by OPERA-3D

B @ central axis



ex) B @ X = 500 axis



The ratio between OPERA and measurement was within goal accuracy of this measurement (1 %).
→ No problem in magnetic field
Upward shift of approximately 0.8% was observed across the entire region.
→miscalibration hall sensors ? Detailed research is ongoing.

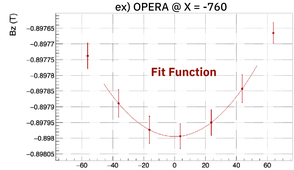
Magnetic Field Integrity Analysis

Definition of Peak

- Using Bz distribution along z-axis
- Fit Function : $p_0(z - p_1)^2 + p_2$ → $\mathbf{p_1}$ **is peak**
- Range : ±50 mm from lowest Bz point

Compare Peak with Every axis
→ can Check solenoidal abnormality

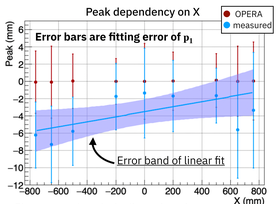
ex) OPERA @ X = -760



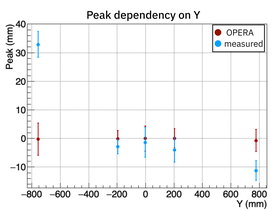
Fit measured peaks by linear function
→ slope is 0.003 ± 0.003
statistically consistent with zero at 5% significance level.
→ no abnormality with solenoidal axis

Magnetic Field Integrity Result

Peak dependency on X



Peak dependency on Y



Relatively flat (Y=-729mm is strange)
Detailed analysis is ongoing

6. Summary

- Detector Solenoid for COMET has been fabricated and delivered.
- Commissioning tests was done and was checked successfull cooling and excitation, shut-down.
- Magnetic field measurement was performed to see good consistency with the simulation by OPERA 3D.
- Solenoidal axis was not inclined apparently.

Systematic Errors to be considered

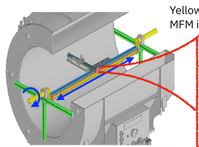
- Mounting angle of hall sensors
- Reproducibility of alignment
- Planer Effect
- Surroundings

Futute MFM : Within Iron Yoke in the experimental condition

We plan to final MFM within the iron yoke & all magnet excited.
This results directly effect to momenum resolution, and our goal accuracy is 10^{-4} T

DS Iron Yoke

New MFM System



Yellow solenoidal axis rotates.
MFM inCylindrical coordinate system.