Superconducting Combined Function Magnet System for the J-PARC Neutrino Beam Line

~ Status of Magnets ~

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KEK

1. Introduction
2. System Overview & Design
3. Development of Quench Protection Scheme
4. Tests for Production Magnets
5. Summary and Schedule
Collaborators

KEK

NIFS
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Mitsubishi Electric.
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BNL (Corrector magnet)
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CEA/SACLAY (Quench Detection & Acquisition System)
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Contents

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Neutrino physics at J-PARC
Tokai-to-Kamioka (T2K) LBL $\nu$ experiment

Objective: study the nature of neutrino in detail

T2K (2009~)

- Off-axis sub-GeV $\nu_\mu$ beam from J-PARC 50GeV-PS
- $\sim 3000 \nu_\mu$ CC int./yr (w/o osc.)
- $\nu_e$ appearance discovery
- $\nu_\mu$ disapp. precise meas.
- 5 year const. Start exp. in 2009
JPARC project and
neutralino beam line

JAERI@Tokai-mura
(60km N.E. of KEK)

<table>
<thead>
<tr>
<th></th>
<th>JPARC</th>
<th>NuMI (FNAL)</th>
<th>K2K</th>
</tr>
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<tbody>
<tr>
<td>E(GeV)</td>
<td>50</td>
<td>120</td>
<td>12</td>
</tr>
<tr>
<td>Int.(10^{12}ppp)</td>
<td>330</td>
<td>40</td>
<td>6</td>
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<tr>
<td>Rate(Hz)</td>
<td>0.275</td>
<td>0.53</td>
<td>0.45</td>
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<tr>
<td>Power(MW)</td>
<td>0.75</td>
<td>0.41</td>
<td>0.0052</td>
</tr>
</tbody>
</table>

$10^{21}$POT(130day) $\equiv$ “1 year”
System Overview

- about 90° bending
- R~105 m
  - Dipole : 2.6 T
  - Quad : 18.6 T/m

Super conducting combined function magnet system
**Combined Function – Merit & Demerit?**

**Merit**
*Reduce ...*
- No. of components
  - 40 → 28
- Cost
  - $>\sim 10\%$ cost reduction (separate function)
- Time & Manpower for Development
  - single magnet design

*Increase ...*
- Beam acceptance
  - $59\pi \rightarrow 69\pi$ (:Increase Q magnet)
- Space between magnets
  - Beam monitor can be installed

**Demerit**
- No example in the world
- Tunnability is restricted

**Note:** need corrector magnets
Dipole and Quadrupole Field Superimposed in a single coil

- Conventional Magnet
  - Inclined iron pole gap
    - KEK-PS Booster
    - BNL AGS

- Superconducting Magnet
  - Dipole and Quadrupole coils assembled in multi-layer coils
    - KEK-B insertion corrector
    - DESY HERA insertion
  - D & Q current distribution superimposed in single layer coil
    - New Proposal for J-PARC neutrino beam line magnet,

Present Work
Contents

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Specification

2+5 Blocks, 41 turns

Pole 20°

Coil ID.: 173.4mm
Mag. Length: 3300 mm
Mech. Length: 3630 mm @RT
Tmax: < 5.0K (Supercritical Helium)
Dipole Field: 2.59 T
Quad. Field: 18.6 T/m
Field Error: < 10^{-3}

Op. Current: 7345 A
Op. Margin: 72%
Inductance: 14.3 mH
Stored Energy: 386 kJ
# of Magnet: 28
SC Cable: NbTi/Cu for LHC arc Dipole Outer-L

50 GeV
Coil Winding for Prototype Magnet

Mirror-symmetry Top & Bottom coils of the prototype
Yoking

Top Collar Installation

Key pushing

Top Yoke Installation

Yoking complete
Shell Welding, Ends Works

Longitudinal shell welding by two automatic welding machines.

End-ring welding

Leads connection by soldering.

Complete
Magnet System with Cryostat

- Combined Function Magnet
  - Dipole 2.6 T
  - Quad 18.6 T/m
  - Produced by single layer coil
- 2 magnets assemble with 1 cryostat
  - F & D magnets (doublet optics)

Reduce cost
- LHC common parts
- Vacuum vessel
- Cold diode
- Support post
- Shield tray

Diagram showing key components:
- SC Busbar
- Iron Yoke
- Stainless Steel Shell (SHV Vessel)
- Lock Key
- Yoke Stack Tube
- L/R Asymmetric Coil
- Plastic Collar
Powering Scheme

- 28 combined function superconducting magnets (dipole and quadrupole in one magnet)
- 14 cryostats (2 magnets per cryostat)
- Magnets in serial
- Focusing and Defocusing magnet
- Cold diode magnet protection
- Necessity of a MSS (Magnet Safety System)
- 6 correction magnets (not on this scheme)
Cryogenic

- Refrigerator Power; 1.2kW@4.5K, 2.5kW@80K
- Supercritical Helium Pump, 300~400 g/s 400kPa
Contents

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4. Tests for Production Magnets
5. Summary and Schedule
Protection Circuit

- Series Excitation of all magnets (~ 0.4 H)
- In the previous protection scheme, magnet is mainly protected by the cold diode.

Dump Circuit
Protect Cold Diodes and SC Bus Bars
Time Constant: 10 sec

Cold Diode
Turn On Voltage: 6V
Forward Voltage: 1V

Powering Scheme
**Protection System**

- **mainly protected by Cold diode**
  1. Once quench starts
  2. Exceed turn-on voltage
  3. Current bypasses to cold diode

Test results:

- **voltage rise was much slower than we expected**
- **Peak Temp. > 500 K from numerical simulation**
Discussion of Quench Protection Scheme

- Al sheet (t=0.1mm, RRR=2000)
  - cover the outside of the coil straight section

- Cu wedge (RRR=200)
  - use copper wedges in the straight section instead of G11 wedges

- Quench protection heater (QPH)
  - attach small sheet heaters
Al sheet & Cu wedges

Al Sheet

Temp. distribution in 0.9 sec after quench

Cu Wedge

Peak Temp. >700 K!
Quench Protection Heater

- Heater size: width 40 mm × height 61 mm
- Quench Detector: 0.1V, 20ms
Quench Protection Heater

- Heater size: width 40 mm × height 61 mm
- Quench Detector: 0.1V, 20ms

QPH is adequate for the conservative quench protection.
QPH ~ number of QPH

Total delay:
Quench detection delay + Thermal diffusion delay

4 QPHs are preferable for the safe protection
Quench Protection Heaters

- **Power supply for QPH**
  - Capacitor Discharge Circuit
  - Energy: 100 J /1 element

![Diagram of Quench Protection Heaters]

- **8 QPH**
- **41 mm**
- **36 mm**

- **120 Ω**
- **120 Ω**

- **350 V**
- **3300 uF**

- **2** (for redundancy)
Full Energy Dump Test

Reassembled 1st prototype

Quench QPH & PS switch-off

Current [kA]

Resistive Voltage [V]

Time [s]

7345 A

Estimated Peak Temp.

~170 K

Acceptable value!
T2K MSS: Principle of quench detection

- 3 MD200 boards for 2 cryostats
- \( \rightarrow21 \) boards for 14 cryostats

Detection Measurement: analog outputs
Detection: logical outputs

Connection box 3-4 with protection resistors
3 high voltage cables with 2 shielded pairs each

Current Beam

Magnet D
Magnet F
Magnet D
Magnet F

= Junction
**T2K MSS : MSS architecture**

MSS: Magnet Safety System

- **Power Supply**: 100 V / 50 Hz
- **Fans**: CMD1, CMD2, CMD3, CLS1, CLS2
- **AC security and distribution**: CALIM1, CALIM2
- **DAQ1, DAQ2**: Rack 1
- **Measurement and detection**: Rack 2
- **UPS**: Power Supply 100 V / 50 Hz
- **Acquisition PC**: Ethernet, Internet
- **Local monitoring PC**: Field bus WorldFIP
- **To remote monitoring PC (+ security protocol)**
- **Triggers**: CII

**Diagram References**
- Local monitoring PC
- Field bus WorldFIP
- Measurement and detection crates
- Triggers CII
- Interface crate
- Safety logic crates
- AC security and distribution
- Rack 1 and Rack 2
Contents

1. Introduction
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Magnet Production

- Three prototype magnets
  - Verification of the magnet design, fabrication tools and assembly procedure.
  - Evaluation of magnet performance such as quench behaviors and magnetic field.

Bidding won by Mitsubishi Electric

- As of February 15, 2007
  12 Production Magnets
  4 Magnet System with Cryostat including prototype
Performance Tests of Production Magnets

- **Quench Tests**
  - in vertical cryostat <- all the magnets
  - in horizontal cryostat <- 2 or 3 magnet system

- **Magnetic Field Measurement (MFM)**
  - at Room Temperature <- all the magnets
  - in LHe <- all the magnets
  - in SHe <- 2 or 3 magnet system
Quench Tests

1. Excitation Tests
2. Quench Protection Heater Check
3. Full Energy Dump Tests
4. Current Bypass Test <- in horizontal cryostat

Up to now
- in vertical cryostat
  - SCFM-01 ~ SCFM-12 (12 magnets)
    - Analyze : SCFM-01~11
- in horizontal cryostat
  - CCFM-00, (CCFM-01 to be tested)
1. Excitation Test at 4.2 K

- \( I_{\text{op}} = 7345 \, \text{A} \) @ 50 GeV (and \( I_{\text{max}} = 7700 \, \text{A} \)) with no quench.
- Fast ramping up to 7345A: No quench at \( 500 \, \text{A/s} \)

No training quench
2. QPH check

Quench Detection Delay (from prototype tests)

Q.D. 0.1V, 10msec $\rightarrow$ 110 msec@7345 A

Current: 4400A

allowable delay $\rightarrow$ <150msec

Meas. Average

$\sim$21.2 ms
3. Full Energy Dump Tests

Example@7345 A

P.S. $R_{\text{dump}} = 0$

Peak Temp. &
Peak Resistive Volt. @ 7345 A

![Graph showing current and resistive voltage over time](image)

![Chart showing peak temperature and resistive voltage against SCFM](chart)
Quench Protection Test with Cold Diode

- Power QPH at F-magnet manually
- Delay extraction circuit to check diode bypass current
- Shut down power supply (dump resistor = 75 m ohm)
Current Bypass to Diode

Peak Temperature in Magnet

- Magnet Current @ It=7kA
- Peak Temperature without Quench Detection Delay
- Peak Temperature with Quench Detection Delay

Current bypass to cold diode is observed as expected
Peak temperatures are well below 200K
→ Very comfortable margin
Contents

1. Introduction
2. System Overview & Design
3. Development of Quench Protection Scheme
4. Tests for Production Magnets
   1. Quench Tests
   2. Magnetic Field Measurement
5. Summary and Schedule
Magnetic Field Measurement

- at Room Temperature (all the magnet)
  - Check → Fabrication Process, Dipole field

- in LHe (all the magnet)
  - Check → Higher order harmonics

- in SHe (2 or 3 magnet system with cryostat)
  - Check → All multipole fields
Field Measurement ~ probe ~

- Use 500mm long rotating coil
- Scanning along magnet bore

GFRP case

Radial coils
Measurement System @ R.T.

*to measure exact dipole field strength*

Need to measure the position of rotating probe

required precision ⇒ $< \pm 0.1\text{mm}$

- Allowable alignment error of the magnet in the beam line: $<\pm 0.3\text{mm}$
Magnetic Field Measurement @ R.T. ~ System ~

- Coincide the magnet central axis with the laser beam
- Measure displacement of the probe from laser beam by PSD

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Position Sensitive Detector (PSD)
Magnetic Field in Straight Section @ 1 A

- Good reproducibility
- Difference: larger than that in B2

Further study is needed.
Magnetic Field Measurement

- at Room Temperature (all the magnet)
  - Check → Fabrication Process, Dipole field

- in LHe (all the magnet)
  - Check → Higher order harmonics

- in SHe (2 or 3 magnet system with cryostat)
  - Check → All multipole fields
Field Measurement in LHe

- Scanning along magnet bore

Probe

Warm Bore
Field Measurement in LHe

- In the vertical cryostat
  - objective: check higher order harmonics
    - Difficult: measure dipole field with good accuracy
    - Difficult: measure the displacement of the probe from magnet axis
  - because of “feed down” from higher order harmonics.

Diagram:
- $o$: rotation axis
- $o'$: magnetic center
- $z_0 = x_0 + iy_0 = r_0 \exp(i\xi)$
  - Feed down: measurement error caused by offset in rotation axis from magnetic center.

Average skew component of quadruple along straight section → 0
**Integral Field Strength @ 7345 A**

- Higher order harmonics $\rightarrow$ small
- 1-2 % difference in B2 $\leftarrow$ ??
MFM System in SHE

- Laser passes through the shaft.

To be tested next month
Summary

- The magnet and magnet system are successfully developed!
  - Quench Protection Scheme

- Magnet and Magnet System Production
  - Almost on schedule (12 magnets, 4 magnet system)
  - Performance -> sufficiently good
    - Field measurement system has to be improved.
## Schedule

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<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
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<tbody>
<tr>
<td>Cryostat w/ 2-SCFMs</td>
<td>1 (proto)</td>
<td>6 (12 Mag.)</td>
<td>6 (12 Mag.)</td>
<td>2 &amp; Install</td>
</tr>
<tr>
<td>Transfer Line</td>
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<td>Refrig.</td>
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<td>PS</td>
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<tr>
<td>Corrector Magnet</td>
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</tr>
<tr>
<td>Quench Detector</td>
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<td></td>
<td></td>
<td>Install</td>
</tr>
</tbody>
</table>
Dipole field measurement

Dipole strength will be measure in the horizontal test stand.

• In the horizontal cryostat: Several magnets will be measured in supercritical helium.

• At the room temperature All the magnets will be measured.

Field measurement system at R.T will be presented in the poster session, MOA08PO02
Alignment of Magnet

- Align the magnet by referring to the alignment markers attached on the magnet.
TOP側アライメントマーカ位置測定(X)のグラフ1

LE PSD ① ② ③ ④ ⑤ RE PSD 測定位置

グラフ 1

HF側アライメントマーカ位置測定(Y)のグラフ2

LE PSD ① ② ③ ④ ⑤ RE PSD 測定位置

グラフ 2

LF側アライメントマーカ位置測定(Y)のグラフ3

LE PSD ① ② ③ ④ ⑤ RE PSD 測定位置

グラフ 3

X(+)

Y(+)

Top側 90°

HF側 180°

0° LF側

270°

Bottom側

LE側から見て