Development of the Superconducting Solenoid for the MuHFS Experiment at J-PARC

Ken-ichi Sasaki,
Michinaka Sugano, Toru Ogitsu, Akira Yamamoto

2011/08/03
Magnet Parameter

- **Requirement for HFS**
  - Field: 1.7 T
  - Local Uniformity: < 1 ppm
  - Uniform Field Region:
    - Ellipsoid
    - \((z:300 \text{ mm}, r:200\text{mm})\)

- **Requirement for g-2**
  - Field: 3 T
  - Local Uniformity: < 1 ppm
  - Uniform Field Region:
    - Cylindrical
    - \((z: \pm 10 \text{ cm}, r:28.3 \sim 33.8 \text{ cm})\)

- **Future application**
  - HFS at higher field?
  - etc....

- **Target**
  - Max. Field: 3.4 T
  - Uniform Field Region:
    - Ellipsoid
    - \((z:300 \text{ mm}, r:200\text{mm})\)
  - Local Uniformity: < 1 ppm
Schematic View

- Build the magnet system in-house at KEK
- Design => almost the same as MRI magnet
  - Superconducting Solenoid with shim coils
  - cooled by LHe with re-condensation cryocooler
    - for long term operation
- Operate in persistent current mode
  - for long time stability (0.01~0.1 ppm /h)
Superconducting Solenoid Design Step

- Magnetic Design
  - Main Coil Configuration: finished
  - Shim Coils Configuration: on going

- Superconducting Design
  - Superconducting Strand Parameters: finished

- Cryogenic Design
  - Heat Load Estimation: finished
  - Re-condensation Cryocooler: on going

- Mechanical Design: on going

- Others
  - Field Monitoring System: on going
  - Test Coil: on going
Main Coil Design

- **Optimized**
  - Coil Current Density: $1.1 \times 10^8$ A/m$^2$
  - 6 main coils and 2 shielding coils

<table>
<thead>
<tr>
<th></th>
<th>Bottom Left R</th>
<th>Bottom Left Z</th>
<th>Top Right R</th>
<th>Top Right Z</th>
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<tbody>
<tr>
<td>MC11</td>
<td>0.3</td>
<td>0.321439</td>
<td>0.356258</td>
<td>0.580432</td>
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<td>MC12</td>
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<tr>
<td>SC11</td>
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<td>0.3</td>
<td>0.73</td>
<td>0.56</td>
</tr>
<tr>
<td>SC12</td>
<td>0.7</td>
<td>-0.3</td>
<td>0.73</td>
<td>-0.56</td>
</tr>
</tbody>
</table>

Ideal coil size w/o shim coils

- 1.5 m
- 1.2 m
- 0.6 m
Magnetic Field by Opera 2d

- $B_{\text{center}} : 3.4000499 \, \text{T}$
- $B_{\text{peak}} : 4.55 \, \text{T}$
- Stored Energy : $\sim 3.4 \, \text{MJ}$

In the Ideal coil size

- Error field from magnet center (T)
  - $2 \times 10^{-6} \, \text{T} = 2/3.4 = 0.588 \, \text{ppm}$
Contents

- Magnet
  - Main Coil Design
  - Quench Protection Study
  - Error Field Study
  - Cryogenic Design
  - Mechanical Design
- Field Monitoring System
- Summary
Quench Protection Study

- To decide the parameters of superconducting cable
  - Quench simulation
  - evaluate **Peak Temperature** and **Peak Voltage** in the coil

- Strand parameters for the calculation
  - $\phi$ 1.5(1.6) mm; Insulation thick.: 50 um; Cu/Sc:6; -> $L = 147.2$ H
  - $\phi$ 1.9(2.0) mm; Insulation thick.: 50 um; Cu/Sc:6; -> $L = 62.9$ H

- Assume simple condition
  - Adiabatic
  - AC loss is neglected
  - Forward V of Diode : 5V
  - Quench starts on MC11
1.6 mm & 2.0 mm Results

1.6 mm:
- Peak Temperature: both OK
- Peak Voltage: 1.6 mm: ~123 K, 2.0 mm: ~132 K

2.0 mm:
- Peak Temperature: both OK
  - 1.6 mm: ~123 K, 2.0 mm: ~132 K
- Peak Voltage: 1.6 mm: 2500 V > 2.0 mm: ~1600 V

Lower voltage is preferable: φ2.0 mm
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Error Field Study

- Evaluated the error field caused by the inaccuracy of the actual winding and structure
  - Non-uniform Current Distribution
  - Position error
  - Deformation
  - Rotation

Non-uniform current

Shift

Deformation

Rotation
Estimated Error Field

- Peak Error Field by actual winding: ± 2 ppm
- Peak Error Field (ppm / 0.1 mm, ppm/ 0.1 mrad)

<table>
<thead>
<tr>
<th></th>
<th>Shift</th>
<th>Deformation</th>
<th>Rotation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>MC11</td>
<td>-7.7</td>
<td>7.7</td>
<td>-38.7</td>
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<tr>
<td>MC21</td>
<td>-0.3</td>
<td>0.3</td>
<td>45.0</td>
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<tr>
<td>MC31</td>
<td>10.4</td>
<td>-10.4</td>
<td>332.3</td>
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<tr>
<td>SC11</td>
<td>0.2</td>
<td>-0.2</td>
<td>0.1</td>
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</tbody>
</table>

Manufacturing Tolerance: 0.1 mm, 0.1 mrad -> 338 ppm

probably inevitable

- Rough correction -> Iron shim
- Fine correction -> Superconducting Shim Coils
Field Correction by Iron Shim

- Estimated the correction power of Iron shim
  - Ring shape
    - Inner radius 0.42 mm; Cross section: 10 mm x 20 mm
### Field Correction by Iron Shim

<table>
<thead>
<tr>
<th>Shim Position</th>
<th>(ppm)</th>
<th>(z^1)</th>
<th>(z^2)</th>
<th>(z^3)</th>
<th>(z^4)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(A_2^0)</td>
<td>(A_3^0)</td>
<td>(A_4^0)</td>
<td>(A_5^0)</td>
</tr>
<tr>
<td>Case 1; (z=0.47)</td>
<td>521</td>
<td>968</td>
<td>1351</td>
<td>349</td>
<td>-5341</td>
</tr>
<tr>
<td>Case 2; (z=0.18)</td>
<td>-91109</td>
<td>-2597</td>
<td>-24598</td>
<td>-90106</td>
<td>-119578</td>
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<tr>
<td>Case 3; (z=0.06)</td>
<td>465921</td>
<td>-16303</td>
<td>13989</td>
<td>467519</td>
<td>1053708</td>
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</tbody>
</table>

- Spherical harmonics expansion
  - Polar Coordinate

\[
B_z(r, \theta, \varphi) = \sum_{n=1}^{\infty} \sum_{m=0}^{n-1} r^{n-1} (n + m) P_{n-1}^m(u) (A_n^m \cos m\varphi + B_n^m \sin m\varphi)
\]

where, \(u = \cos \theta\)
Superconducting Shim Coil ~ Zonal Coil Model

- Assume ideal circular current
  - $n=1$ (z$^1$ coil)
  - $n=2$ (z$^2$ coil)
  - $n=3$ (z$^3$ coil)
  - $n=4$ (z$^4$ coil)

Zonal shim coils could be composed of 2 or 4 circular currents
Zonal Shim coil ~ harmonic coefficient

\[ B_z = A_1^0 + 2A_2^0 z + 3A_3^0 z^2 + 4A_4^0 z^3 + \cdots \]

- Bz on z axis generated by circular currents in radius of 0.4 m

<table>
<thead>
<tr>
<th></th>
<th>z1</th>
<th>z2</th>
<th>z3</th>
<th>z4</th>
<th>(z4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Coil</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>49.1066°</td>
<td>40.0889°</td>
<td>33.8782°</td>
<td>29.3385°</td>
<td>53.7222°</td>
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<tr>
<td>( \alpha_2 )</td>
<td>-</td>
<td>73.4273°</td>
<td>62.0404°</td>
<td>53.7222°</td>
<td>77.9187°</td>
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<tr>
<td>C_0</td>
<td>-</td>
<td>0.3033</td>
<td>0.2809</td>
<td>0.2245</td>
<td>0.5603</td>
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<tr>
<td>Length in Z</td>
<td>0.693 m</td>
<td>0.950 m</td>
<td>1.192 m</td>
<td>1.423 m</td>
<td>0.587 m</td>
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<tr>
<td>( A_1^0(z^0) )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>( 2A_2^0(z^1) )</td>
<td>5.036e-6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>( 3A_3^0(z^2) )</td>
<td>0</td>
<td>10.5698e-6</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>( 4A_4^0(z^3) )</td>
<td>0</td>
<td>0</td>
<td>19.4982e-6</td>
<td>0</td>
<td>0</td>
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<td>-114.652e-6</td>
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<td>( 6A_6^0(z^5) )</td>
<td>-100.95e-6</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>( 7A_7^0(z^6) )</td>
<td>0</td>
<td>-265.06e-6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
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- Field Monitoring System
- Summary
Cryogenic Design

- Heat Load Estimation
  - Conductive Heat
    - Coil Support Rod
    - Current Leads
  - Radiation Heat

• Total Heat Load

<table>
<thead>
<tr>
<th>Case</th>
<th>No. of GM cooler</th>
<th>He vessel (W)</th>
<th>Thermal shield (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1</td>
<td>1.77</td>
<td>75.24</td>
</tr>
<tr>
<td>Case 2</td>
<td>2</td>
<td>0.62</td>
<td>78.63</td>
</tr>
</tbody>
</table>

One GM cryocooler -> no enough margin

**Two 2-stage GM cryocoolers**
Contents

- Magnet
  - Main Coil Design
  - Quench Protection Study
  - Error Field Study
  - Cryogenic Design
  - Mechanical Design
- Field Monitoring System
- Summary
Mechanical Design

- **Overview**

- Vacuum Vessel
- Heat Exchanger
- Main Coil
- Thermal Shield
- Warm Bore
- Cryocooler and Current Lead
- He Vessel
- Active Shield Coil

Dimensions:
- 1.45 m
- 1.7 m
- 2.5 m
- 1 m
Mechanical Design ~ Coil Bobbin Design

- For the precise magnet design
  - must consider coil deformation
    - Winding tension
      - 100 ~ 500 um depending on the tension
    - Thermal contraction during cooling
      - ~ 2.8 mm at a maximum
    - Hoop stress during excitation
      - 27 ~ 30 MPa
Contents

- Magnet
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  - Mechanical Design
  - Cryogenic Design
- Field Monitoring System
- Summary
Precise Field Monitoring System

- NMR probe
- Require 3-axis moving stage \((r, \theta, z)\)
  - built the prototype stage
In order to achieve the high stability and accuracy, the frequency of the RF signal to the NMR sample has to be stabilized.

- Reference Frequency Generator with GPS
  - Accuracy: <10^{-12}
  - Stability: <10^{-11}/day

- Function Generator

- NMR unit + EFM-07
  - $F_{FG}$ check

- PreAmp 1
  - $F_0 = F_{FG} \times 10$

- PreAmp 2

- 7.5 digits Voltmeter
  - $V_{\text{read}}$ in proportion to $\Delta B$ from $B_0$
    - ($B_0$ defined by $F_0$)

- 12 digits Frequency Counter

- Sample: Rubber
Stability of NMR system in 3T magnet test

- **Input Frequency**: 12,771,271.534 Hz (~ 2.9996145 T)
  
  \[ F_{FG} \]
  
  \[ \sigma_B = 1.4 \times 10^{-4} \text{ ppm} \]

- RF signal of the function generator seems to be highly stabilized due to the reference frequency generator.

- Deviation of the output voltage is larger than input RF signal.
  - Measurement error of voltmeter.
  - Signal modulation in the NMR unit and the pre amps.

To decrease the noise -> New NMR unit
RF signal could inputs directly into the NMR probe
Accuracy of NMR system

- The output voltage “must” be linear with the input frequency, when the field is measured at a fixed point.

**Correlation between ΔV and ΔF**

- Error from the linear regression line : ± 1 ppm
- NMR unit might have any problem in the electrical circuit.
  
  -> In the next test, we will investigate the reasons in more detail.
Summary ~ Plan

- Magnet design:
  - Many design steps are steadily proceeded in parallel
  - Main Coil Design: Ideal coil geometry was obtained
    - 6 main coils and 2 active shield coils
  - Quench Protection Study
    - Strand Diameter: $\phi 2$ mm, Cu/Sc = 6
  - Error Field Study
    - Manufacturing Tolerance: 0.1 mm, 0.1 mrad -> 338 ppm

- Mechanical Design
  - on going

- Cryogenic Design
  - Estimated heat load -> Two GM cryocoolers are required

- Field Monitoring System
  - developing the moving stage
  - try to improve the stability and accuracy
Next step

- Test coil winding
  - in this summer
- Shim coil design
  - practical design of zonal shim coils
  - design tesseral shim coil
- Field Monitoring System
  - upgrade the moving and NMR system

Magnet system will be ready in the end of March, 2013