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- Fabrication of the HTS dipole magnet
- Field measurement of the HTS dipole magnet
- Prospect
- Conclusion
KEK has engaged in “HTS” R&D program supported by “Japan Agency for Medical Research and Development (AMED)”

R&D of **HTS-based** rotating gantry for Carbon-Ion Radiation Therapy

Collaboration w/ **Toshiba Co., Ltd.** and **Kyoto Univ.**
GANTRY FOR CIRT

- **Gantry:**
  - Composed of group of magnets: dipole, quadrupole, scan magnets, etc
  - Can deliver beam to a tumor from a number of direction
  - Can avoid rotating a patient
- **Carbon-ion (C^{6+}) Radiation Therapy (CIRT):**
  - Good relative biological effectiveness (RBE): **6 times larger** than that of proton beam
  - **Less multiple scattering** and **sharper Bragg peak** than those of proton beam
  - Easily handle the size/local dose of the beam

**Gantry+CIRT = Powerful & Effective tool**
C\textsuperscript{6+} requires \textbf{larger} beam rigidity as compared to proton beam (T\textsubscript{carbon}= 430MeV/u)

- Beam rigidity : \( R\text{\textsubscript{carbon}}=6.57 \text{T}\cdot\text{m} \)
  - \( = 3 \times R\text{\textsubscript{proton}} (=2.43 \text{T}\cdot\text{m}) \)
  - "High field" or "Large acceptance" is \textit{essential}

- Two CIRT gantries in the world at present
  
  - \textbf{NC gantry @ HIT in Gereman:}
    - \( B\text{\textsubscript{dipole}}=1.8\text{T}, \ L\text{\textsubscript{gantry}}=25\text{m}, \ M\text{\textsubscript{gantry}}=600\text{t} \)
  
  - \textbf{SC gantry @ NIRS in Japan:}
    - \( B\text{\textsubscript{dipole}}=2.9\text{T}, \ L\text{\textsubscript{gantry}}=13\text{m}, \ M\text{\textsubscript{gantry}}=210\text{t} \)
Past study showed “HTS” could play an effective role in further reduction of the size:
- Gantry length: 9.2 m
  - (ref. NC: 25 m, LTS: 13 m)
- Total weight: 177 t
  - (ref. NC:600 t, LTS:210 t)

**Promotion of the widespread adoption of CIRT gantry**

### Design of the HTS (dipole) magnet for gantry:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil mechanical length</td>
<td>540 mm</td>
</tr>
<tr>
<td>Dipole field</td>
<td>5.8 T</td>
</tr>
<tr>
<td>Bore radius</td>
<td>30 mm</td>
</tr>
<tr>
<td># of layers</td>
<td>4</td>
</tr>
<tr>
<td>Field quality</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Reference radius</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

Investigation of feasibility of HTS magnet for CIRT gangry

- Establish the winding technology for the HTS dipole magnet using ReBCO coated conductor (4mm wide)

- Estimation of effect from the shielding current on the field uniformity

- Fabricate the model magnet @ Toshiba
  - Make coils based on the established technology
  - Check its performance and healthiness after the winding process
  - Check its field quality using harmonic coil system

**Prospect:**
- Development of quench protection
OUR TASK

Investigation of feasibility of HTS magnet for CIRT gangry

- Establish the winding technology for the HTS dipole magnet using ReBCO coated conductor (4mm wide)

- Estimation of effect from the shielding current on the field uniformity

- Fabricate the model magnet @ Toshiba
  - Make coils based on the established technology
  - Check its performance and healthiness after the winding process
  - Check its field quality using harmonic coil system

Prospect:
- Development of quench protection

N. Amemiya et al.,
FABRICATION
Model magnet

**Dipole field**: 3.0 T

**Rated current**: 366 A

**Load line ratio**: ~60% @ 20K

**Bore radius**: 30 mm

**Num. of HTS coils**: 24

**Num. of coil turns**: 50

**Coil inductance**: 288.9 mH

**Reference radius**: 20 mm

**Field quality**: 0.2%

Magnet is designed to be cooled down to 4K by means of conduction-cooling method.
Coil was wound through the automated winding machine developed by Toshiba

- Turn-to-turn insulation: prepreg tape inserted in-between ReBCO tapes
- Winding accuracy was measured to be $0.2\text{mm}$
- Effect on the field uniformity was confirmed be negligible according to 3D FEM calculation

Healthiness of each coil was confirmed by checking its I-V characteristics at 77K

Each coil is connected to a refrigerator through a high-purity aluminum sheet which is attached to a surface of the coil.

HARMONIC COIL SYSTEM

- Requirements:
  - Sampling rate for multipole measurement is 10 Hz
  - i.e. Maximum rotation speed of the coil is 10 rot/s
  - Measure multipole coefficients with a precision better than 0.1% to confirm good field uniformity of <0.1% @ 10 Hz samples/s
  - Enable to measure coefficient on the on-line basis
There are two institutions at which carbon-ion radiotherapy (CIRT) is performed. This phenomenon might be explained by the properties of the carbon ions, which have been studied well over decades. There are two institutions at which carbon-ion radiotherapy (CIRT) is performed. This phenomenon might be explained by the properties of the carbon ions, which have been studied well over decades.

The magnet is designed to be cooled by means of a laser displace meter, and its effect on the field uniformity was measured. The surface of the mandrel was measured for each turn using a laser displace meter, and its effect on the field uniformity was measured. The surface of the mandrel was measured for each turn using a laser displace meter, and its effect on the field uniformity was measured.

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Development of the measurement system for the magnetic field of the gantry magnet made of 143T. The field in "three-blocks" coil was found to be larger than 10^-2 mm.

Harmonics & sextupole (b_n) and sextupole (b_n) were measured. Computation of harmonics (N+1) and sextupole was carried out with numerical simulation (OPERA-3D) was then carried out with numerical simulation (OPERA-3D) was then carried out with numerical simulation (OPERA-3D).

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FIELD MEASUREMENT
Ramp-rate was set to $<5\text{A/min}$

- Maximum field of $1.2\text{T}$ was achieved at $I=153\text{A}$ so far (see left fig.)
- Operation was suspended at $B=1.2\text{T}$ since spikes of coil voltages were observed
  - One of the examples is shown on right fig., where a coincidental field jump (~100 ppm) is also seen (Flux jump?)

- **Effect from this jump could be significant when increasing operation current.**
- **In addition, 100 ppm change is already critical for particle accelerator application ($\sim10^{-4}$)**

Need some countermeasures
- Left: Field harmonics (normal) at $R_{\text{ref}}=20\text{mm}$
- Right: Deviation from the center field along horizontal direction
- Operating current was fixed at 120A ($B=1.0\text{T}$)
- Large contribution from $b_2$ and $b_3$: $O(10^{-2})$
- Field non-uniformity is limited to 2%
MIS-ALIGNMENT ISSUE

- Why observed large non-uniformity?
  - Mis-alignment during the fabrication process, especially “coil layering”
  - The mis-alignments of the coils were reproduced in the 3D calculation, showing similar trend in deviation of quadrupole
  - Allowed multipoles, however, do not show any deviation, indicating our understanding on the mis-alignment is not perfect

Further investigation needs to be made, but this result provides useful information for the next design study
- Harmonics (allowed multipoles) along the longitudinal direction
- Effective length
  - Data: **286.6 mm**
  - Calculation: **274.4 mm**
  - Agree within 2% level
- Although large discrepancy is observed in $b_3$ around the magnet center ($Z \sim 0$), overall profile is consistent with the calculation
PROSPECT
TEST AT KEK

- We plan to continue the ramp-up test at KEK
- The magnet was delivered from the Toshiba Factory
- Ready to start the operation
- Investigation of the flux-jump like events
- Investigation of the large non-uniformity
- Temporal evolution of the screening current
- etc...
Collaboration project for R&D of HTS-based gantry
Model magnet was fabricated at Toshiba, and its performance was measured using the harmonic coil system
Flux-jump like event, which could be a critical issue for application, was observed during the ramp-up test
Non-uniformity was limited to 2%, the reason of which partially be explained by mis-alignment of the coils
We plan to continue the measurement
SUPPLEMENT
KEK “HTS” ACTIVITY

- KEK has engaged in “HTS” R&D program supported by “Japan Agency for Medical Research and Development (AMED)”
- Brief introduction to AMED

Japan Agency for Medical Research and Development aims to act as a 'control tower' that directs integrated research, from basic research to practical application. And since Japan is projected to become the world's first ultra-aging society, AMED aims to achieve the world's healthiest and longest-living people by creating the world's most advanced medical technologies and services, and also aims to become a pillar of Japan's economy by fostering medicine, drugs, and medical devices as strategic industries.

Fig. 1. Layout of the HTS-based gantry [3]. In the figure, "STR" and "SCM" represent the steering and scanning magnets, respectively.

TABLE I

<table>
<thead>
<tr>
<th>Saddle-Shape Coils Design</th>
<th>Coil Inner Aperture type</th>
<th>Radius (mm)</th>
<th>Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>60</td>
<td>7.33</td>
<td>-</td>
</tr>
<tr>
<td>A2</td>
<td>21.58</td>
<td>17.42</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>36.71</td>
<td>32.55</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>60.11</td>
<td>55.95</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>65</td>
<td>7.33</td>
<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>21.58</td>
<td>17.42</td>
<td></td>
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</tr>
<tr>
<td>B4</td>
<td>60.11</td>
<td>55.95</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>70</td>
<td>7.33</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>21.58</td>
<td>17.42</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>36.71</td>
<td>32.55</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>60.11</td>
<td>55.95</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>75</td>
<td>7.33</td>
<td>-</td>
</tr>
<tr>
<td>D2</td>
<td>21.58</td>
<td>17.42</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>36.71</td>
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</tr>
<tr>
<td>D4</td>
<td>60.11</td>
<td>55.95</td>
<td></td>
</tr>
</tbody>
</table>

In order to avoid enlarging irradiation area around the target tissue, non-uniformity of the dipole field is restricted to less than $10^{-3}$ at the reference radius of 20 mm. YBCO CC (SuperPower Ltd.) is used as the HTS material, where the thickness and width of the tape are 0.1 mm and 4.0 mm, respectively. In order to wind the CC onto the designed saddle shape while minimizing edgewise bending, we adopt "constant-perimeter condition" [4]. A schematic of the dipole magnet with the saddle-shaped coils is displayed in Fig. 2 (a). The dipole magnet is composed of 32 saddle-shaped coils in total: 16 different coils each sit at one side of the poles so that the number of blocks for each layer is arranged into 4 per quadrant. In this way, a four-layer dipole magnet with a $\cos \theta$-current distribution is formed.

Specifications of these 16 different coils are summarized in Table I. The non-uniformity of the dipole field with this magnet design is estimated to be $<10^{-3}$ at the reference radius of 20 mm according to a 3D numerical simulation (OPERA-3D). The magnet is also designed to be cooled by means of the conduction-cooling method as it is difficult to use coolant for the rotating gantry; each of the coils is connected with a refrigerator through a high-purity aluminum sheet.

After the design study, we decided to construct a dipole magnet based on the design described above. This magnet is a short model of the actual design: a length of the straight part is set to 100 mm, which corresponds to 1/3 of the actual one. During the course of the construction of the model magnet, however, we found the space was too limited to insert the first block (corresponding coil types are A1, B1, C1, and D1). So we determined to construct "three-blocks" coil whose schematics and specification are shown in Fig. 2 (c) and Table I, respectively. The effect of altering the coil configuration was studied using the OPERA-3D simulation. Although non-uniformity of the field in "three-blocks" coil was found to be larger than $10^{-3}$, we proceeded the field measurement of the model magnet to ensure the performance of the assembled one is consistent with results from the simulation. Details of the field measurement are described in Section V.

TABLE II

Main parameter of the model magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole field strength</td>
<td>3 T</td>
</tr>
<tr>
<td>Rated current</td>
<td>366 A</td>
</tr>
<tr>
<td>Bore radius</td>
<td>30 mm</td>
</tr>
<tr>
<td>Inner radius of iron yoke</td>
<td>95 mm</td>
</tr>
<tr>
<td>Outer radius of iron yoke</td>
<td>205 mm</td>
</tr>
<tr>
<td>Num. of HTS coils</td>
<td>24</td>
</tr>
<tr>
<td>Num. of turn for each coil</td>
<td>50</td>
</tr>
<tr>
<td>Magnet mechanical length</td>
<td>1200 mm</td>
</tr>
<tr>
<td>Coil mechanical length</td>
<td>340 mm</td>
</tr>
<tr>
<td>Coil inductance</td>
<td>288.9 mH</td>
</tr>
<tr>
<td>Sum of Lorentz force per quadrant</td>
<td></td>
</tr>
<tr>
<td>Horizontal ($\Sigma F_x$)</td>
<td>349.4 kN/m</td>
</tr>
<tr>
<td>Vertical ($\Sigma F_y$)</td>
<td>-74.7 kN/m</td>
</tr>
</tbody>
</table>

MODEL MAGNET ASSEMBLY

Table II shows a specification of the "three-blocks" model magnet. This magnet is designed to produce a dipole field of 3 T at 4 K. Design of the iron yoke and the cryostat for the model magnet is based on that used in the LTS-based gantry magnet.

Each of the saddle-shaped coils was made through an automated winding machine which was developed by Toshiba Co., Ltd. A photograph of some fabricated coils is shown in the left of Fig. 3. Note that, in the picture, the mechanical mandrel which was used during the winding process is replaced with the isomorphic acrylic cylinder for the visualization. After the coil winding, displacement of the tape from a surface of the
I-V CHARACTERISTICS

S. Takayama et. al.,
- Coil voltage is integrated during an interval between the arrival time of the encoder pulses ($T_k$, $T_{k+1}$) (see right picture)
- Two integration methods are possible
  - Riemann integral
  - Trapezoidal rule
→ Adopt “trapezoidal rule” for better resolution

- Coil voltage at the arrival time of the encoder pulse ($V_k$) is determined from a linear interpolation between two neighboring voltages ($S_i$, $S_{i+1}$)
  - $V_k = S_i + (S_{i+1} - S_i)/(t_{i+1} - t_i) \times (T_k - t_i)$
- According to simulation:
  - Confirmed a precision better than 0.1% is achievable for multipole measurement if DAQ device has:
    • >500kHz for ADC sampling rate
    • >16bit for ADC resolution
    • >40MHz clock Hz (for encoder pulse)
Further investigated if the inconsistency in the x-mapping are due to ‘mis-alignment’ of the rotating coil

Assume the coil was mis-aligned by 0-5mm

Best agreement was found at (dx, dy)=(0mm, -2mm)

Inconsistency in x-mapping is considered to be due to mis-alignment

In summary, we ensured our measurement system has a measurement precision (<0.1%) for multipoles with a fast (7Hz) sampling rate
HARMONICS

\[ \frac{b_n}{b_1} \times 10^{-3} \]

<table>
<thead>
<tr>
<th>Multipole order (n≥2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
</tr>
<tr>
<td>data</td>
</tr>
</tbody>
</table>

Skew normalized to \( b_1 \)

\[ \frac{\text{Skew normalized to } b_1}{b_1} \times 10^{-3} \]

<table>
<thead>
<tr>
<th>Multipole order (n≥1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>data</td>
</tr>
</tbody>
</table>

Difference

\[ \times 10^{-3} \]

<table>
<thead>
<tr>
<th>Multipole order (n≥2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
</tr>
<tr>
<td>OPERA-3D</td>
</tr>
</tbody>
</table>

\[ \times 10^{-3} \]

<table>
<thead>
<tr>
<th>Multipole order (n≥1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>OPERA-3D</td>
</tr>
</tbody>
</table>
COIL MISALIGNMENT

ミスマラジメント（z軸に対する回転）

高山さんの資料から、コイル設置位置の変位を計算します。

A4（上）は固定されているとした。
A3の回転角度を計算すると、上下コイルともに2°程度と考えられる。
A2下コイルについては、実は元の位置からそこまで動いていないのではないかと考えられる。
問題なのはA2上コイル。表を見ても1層目と2層目で傾向が異なるため、変位を推測することが難しい。これについては完全に不定性扱いとし、今回の見積もりではA2上コイル同様、元の位置から回転していないと仮定して進める。なお、3、4層目は1、2層目と同じように回転しているもの仮定する。
Understand E-J characteristics for ReBCO tape

15.5 T magnet @ Tohoku Univ.