An integral magnetic field measurement system is designed to meet the requirement of the HUST-PTF consists of a 250 MeV isochronous superconducting cyclotron, three treatment rooms and one experimental station. The beamline layout is shown in Fig. 1. An integral magnetic field measurement system is designed to meet the requirement of the beamline dipole magnets.

Background

- Cancer is the leading cause of death in China and is also a major public health problem. Proton therapy offers a substantial clinical advantage over conventional photon therapy.
- A new proton therapy facility (HUST-PTF) is under construction in Huazhong University of Science and Technology (HUST), which is supported by National Key Research and Development Program of China.
- HUST-PTF consists of a 250 MeV isochronous superconducting cyclotron, three treatment rooms and one experimental station. The beamline layout is shown in Fig. 1.
- An integral magnetic field measurement system is designed to meet the requirement of the beamline dipole magnets.

The uniformity of integral field and the dispersity among the batch of 30-degree dipoles of the beamline should be achieved used: 30-degree dipoles, 60-degree dipoles and 90-degree dipoles. We take the 30-degree dipoles as example to describe the design of the measurement system.

Design principle

The most critical parameters of the long coil are the number of turns, width, and length. Usually the length can be determined by the empirical formula. About the turns and the width, some aspects should be considered:

- an acceptable signal-to-noise ratio.
- excessive induced voltage should be avoided.
- the sextupole component should be eliminated.

The length of the long coil: \( L_c \geq L_{c0} + 8G \)

The induced voltage of the long coil: \( V_c = 31.4BL_d dB/dt \)

The flux linkage of sextupole component:

\[
\Phi_s = \int \left[ \frac{1}{2}y \cdot \Phi \right] dx = \frac{3}{2}y_a d_a (y^2 - x^2) / 2
\]

The long coil will be wound in one layer with single strand enamelled wire with a diameter of 0.1 mm. The induced voltage of the long coil should be limited to 0.5% to make sure it has an applicable signal-to-noise ratio, while it will not exceed 70% of the voltage integrator input range.

According the expression, when we choose the width of the long coil equals to the height of the long coil, the sextupole component can be eliminated. According to the analysis above, we can have the parameters of the long coil for 30-degree dipole magnets.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Quantity</th>
<th>Unit</th>
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<tbody>
<tr>
<td>B</td>
<td>0</td>
<td>Tesla</td>
</tr>
<tr>
<td>( y_0 )</td>
<td>0</td>
<td>mm</td>
</tr>
<tr>
<td>( y_a )</td>
<td>0.1</td>
<td>mm</td>
</tr>
<tr>
<td>( d_a )</td>
<td>0.1</td>
<td>mm</td>
</tr>
<tr>
<td>( d )</td>
<td>0.1</td>
<td>mm</td>
</tr>
<tr>
<td>( L_{c0} )</td>
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<td>mm</td>
</tr>
<tr>
<td>( L_d )</td>
<td>100</td>
<td>mm</td>
</tr>
</tbody>
</table>

Long coil model

The framework of the long coil is elastic, so we can manufacture it straight first, and then inlay it into the arc groove.

Analysis

The integral magnetic field measurement system should design well to reduce errors and achieve higher accuracy to meet the requirement of the dipole magnets. Some major influences are discussed, including the ambient temperature, the width and the alignment of the long coil, the drift of the voltage integrator, and the instability of the magnet power supply. It will help to control the errors and achieve higher accuracy.

We use relative error of magnetic flux, for it can achieve higher accuracy of ~10⁻⁵. The relative error \( E(x) \) is used to express the integral field uniformity:

\[
E(x) = \frac{\Phi(x) - \Phi(0)}{\Phi(0)}\times 10^{-5}
\]

Calculation

\[
\Phi(x) = \int \int (B_x) dx dy = \int \left[ \frac{1}{2} y \cdot \Phi \right] dx = \frac{3}{2} y_a d_a (y^2 - x^2) / 2
\]

Measurement system

- A high-precision integral magnetic field measurement system is designed, which could be used for all three types of dipole magnets.
- The detailed hardware design scheme and the mechanical structure are described.
- The long coil is the key part of the measurement system, and the design of the long coil is illustrated.
- To meet the requirement of dipole magnets, the errors are also discussed. Based on some simplifications, we derived simple and analytical expressions to describe the effects of ambient temperature, the width and the alignment of the long coil, the drift of the voltage integrator, and the stability of the magnet power supply. It will help to control the errors and achieve higher accuracy.
- The whole system of dipole magnets can fulfill the integral measurement efficiently and reliably. The measurement of the prototype magnets is planned to be carried out in 2018.

Hardware design scheme

- We use relative error of magnetic flux, for it can achieve higher accuracy of ~10⁻⁵.
- The relative error \( E(x) \) is used to express the integral field uniformity:

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\]

Conclusion

- Two high-precision motion stages are placed beside the dipoles separately to fit the different size of dipoles.
- The motion stages support the long coil, and the control system and servo unit ensure both stages can move the long coil synchronously.
- The alignment support is designed to adjust the reference plane, which can provide an extremely high-precision plane for the long coil.
- Granite is used for the reference plane and the motion stages. It can provide higher accuracy during the measurement.