MT25
25th International Conference on Magnet Technology
[MT25-Thu-Af-Po4.11-04]

The Design of Integral Magnetic Field Measurement System of Dipole Magnets for HUST-PTF

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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.

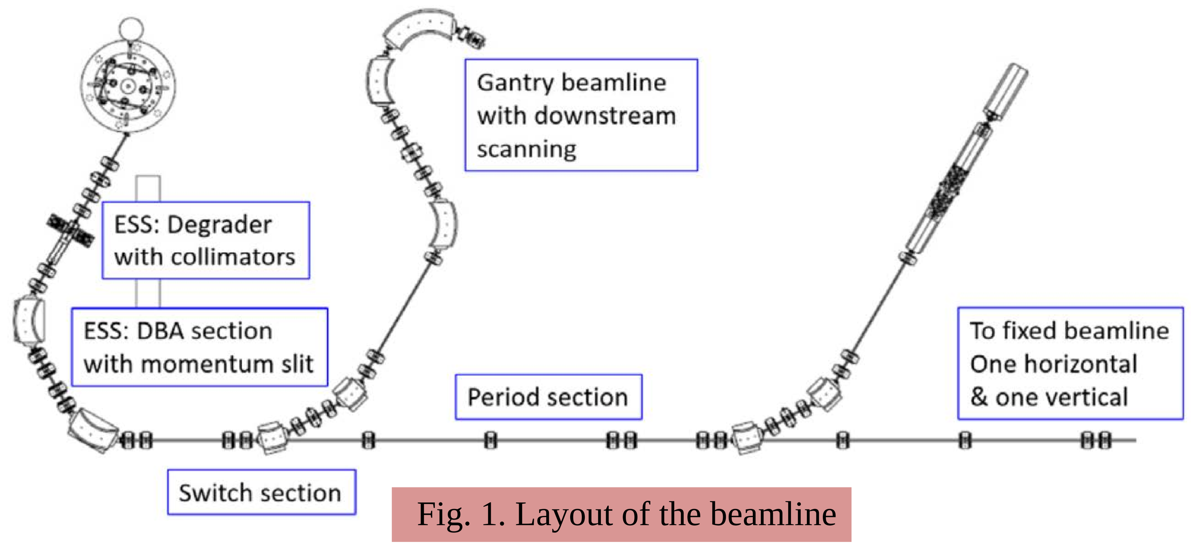

Fig. 1. Layout of the beamline

Conclusion

- 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 planed to be carried out in 2018.

Measurement system

According to the beamline design, three kinds of dipoles are 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.

The uniformity of integral field and the dispersity among the batch of 30-degree dipoles of the beamline should be achieved by the measurement system.

TABLE I 30-DEGREE DIPOLE SPECIFICATIONS

Dipole parameters	Quantity	Unit
Bending angle	30	degree
Bending radius	1500	mm
Magnetic field	0.82-1.62	T
Pole gap	60	mm
Pole width	250	mm
Good field region	±40	mm
Integral field uniformity	$<8\cdot10^{-4}$	
Harmonic error	$<5\cdot10^{-4}$	

Hardware design scheme

The integral magnetic field measurement system:

- FDI2056 fast digital integrator
- Industrial PC(IPC)
- NI digital voltmeter(DVM)
- Danfysik magnet power supply
- Renishaw high-precision grating ruler
- Yaskawa servo unit
- Digital display meter
- High-precision Motion stage
- Ultrastab Saturn Current Transducer

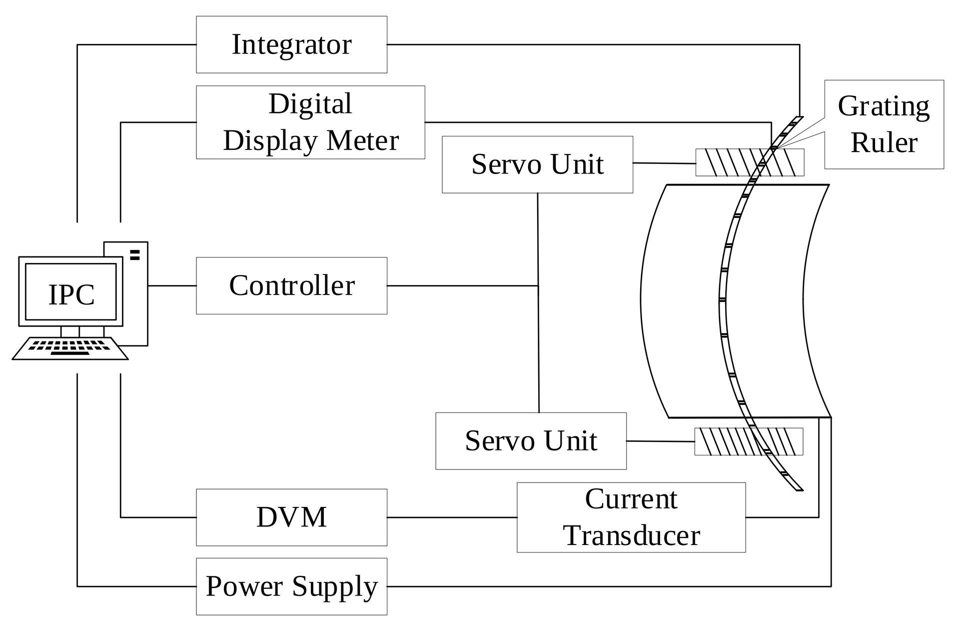

Fig.2. Hardware design scheme of the measurement system.

Measurement mechanism

- 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:

$$E(x)=\left[\Phi(x)-\Phi(0)\right]/\Phi(0)$$

$\Phi(0)$ is the magnetic flux of beam central orbit.

$\Phi(x)$ is the magnetic flux at the position x in radial.

$[\Phi(x)-\Phi(0)]$ can be obtained by moving the long coil.

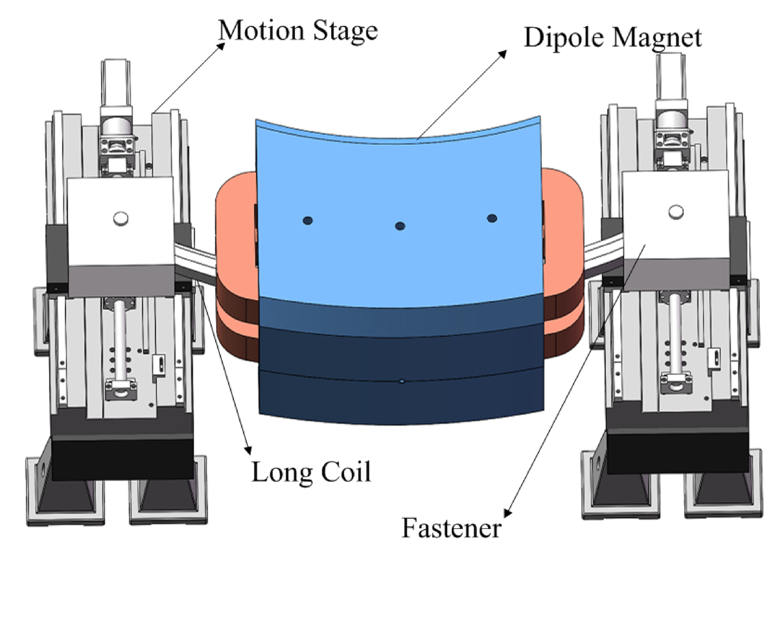

Fig.3. Mechanical structure of the measurement system.

- 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.

Design of the long coil

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 : $L_c \geq L_m + 8G$

The induced voltage of the long coil: $V_c = NWL_c dB/dt$

The flux linkage of sextupole component:

$$\Phi_3=\iint a_3\left(x^2-y^2\right)L_c dxNdy/(2h)$$
$$=2a_3NLd\left(d^2-h^2\right)/3$$

- L_c = length of long coil
- W = width of long coil
- N = number of turns

The long coil will be wound in one layer with single strand enameled wire with a diameter of 0.1 mm.

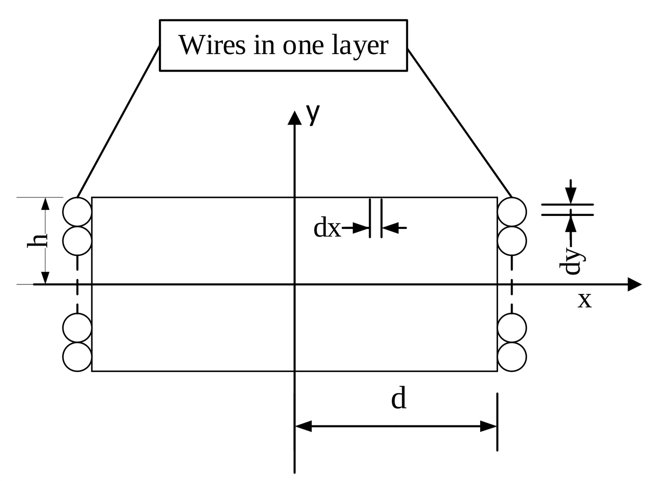

Fig.4. Cross section of the long coil.

- d = half width of long coil
- h = half height of long coil
- L_m = length of dipole
- G =height of dipole aperture.

Long coil model

The induced voltage of the long coil should be limited to 0.35V to make sure it have 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.

L_c /mm	N	W/mm
l300	100	10

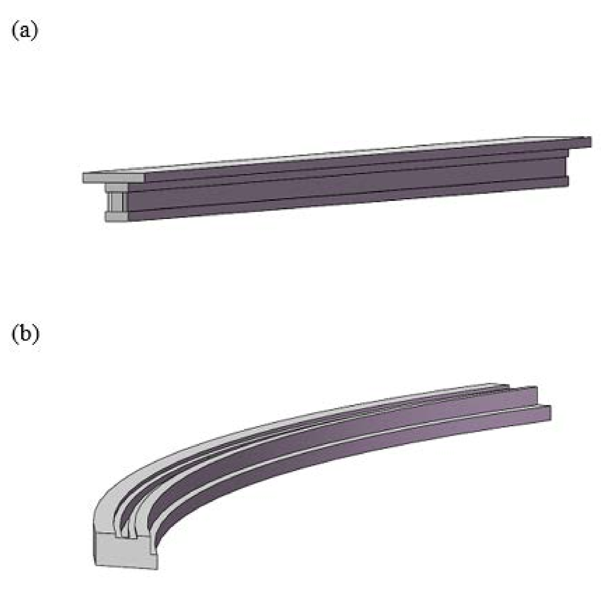

Fig.5. (a) Framework. (b) Arc groove.

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

Error analysis

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.

Based on some simplifications, we derived simple and analytical expressions to describe the effects of these errors. It will help to calculate the parameters to control the errors and achieve higher accuracy.

Example: requirement of the measurement (30-degree dipole magnets)

Ambient temperature	±1℃
Framework width	≤0.1%
Angle of inclination	≤20mrad
Stability of magnet power supply	~10-6
Drift of integrator (FDI2056)	No effect with certain method

Calculation

Ambient temperature:

$$\Delta\Phi/\Phi=NB\left[(L+\Delta L)(W+\Delta W)-LW\right]/(NBLW)$$

$\alpha=(\Delta L/L_0)\Delta T$

α=coefficient of thermal expansion

Framework width:

$$\Delta\Phi/\Phi=\int_{L_{edge}}^{L_{edge}+L_{cent}} NB\left[W(z)-W_0\right]dz \,/\, NB\int_{L_{edge}}^{L_{edge}+L_{cent}} W_0 dz$$
$$=\Delta W/(2W_0)$$

L_{edge}=length of end field
L_{cent}=length of main field

Angle of inclination:

$$\Delta\Phi/\Phi=[NW\int Bdz-NW\int B\cos\theta dz]/(NW\int Bdz)$$
$$=1-\cos\theta$$

θ=length of end field

Stability of power supply:

$$\Delta\Phi/\Phi=NW\left[\int F(I+\Delta I)(I+\Delta I)dl-\int F(I)Idl\right]$$
$$/\left[NW\int F(I)Idl\right]$$

F(I)=transfer function

Drift of integrator:

$$\Phi_{drift}/\Phi=\int U_{drift}dt\Big/\left(NW\int B(z)dz\right)$$

Udrift= drift of integrator

Comprehensive error:

$$\Delta\Phi/\Phi_0=\left(\frac{\Delta I}{I}+\alpha\Delta T+\frac{\alpha\Delta I\Delta T}{I}\right)\cos\theta+\left(\frac{\Delta W}{2W_0}+\frac{1}{2}\cdot\frac{\Delta W}{W_0}\cdot\frac{\Delta I}{I}\right)\cos\theta+(\cos\theta-1)$$