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METHODS AND ERROR ANALYSIS OF HELIUM PIPE TEMPERATURE MEASUREMENT IN THE EAST SUPERCONDUCTING MAGNET SYSTEM

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【Abstract】 In the EAST (abbr. Experimental Advanced Superconducting Tokamak) device, operational temperature of the SC (abbr. superconducting) magnet system is closely related to those issues like thermal load calculation and SC performance and operational stability. Temperature on He (abbr. Helium) cooling pipe is required to achieve accurate measurements in the SC magnet system. The paper focuses on methods and error sources and their influence on He pipe temperature measurement. It also puts forward some methods to reduce errors and the good experimental results which help satisfy engineering requirements. The methods discussed in the paper can be applied to all the cryogenic weak signal measurements.

Keywords: EAST SC magnet system, He pipe temperature measurement, error sources

PACC: 0720, 0750

1 INTRODUCTION

EAST, a fully SC tokamak device, aims at studying physical and technical issues in steady tokamak fusion device[1]. The EAST SC magnet system consists mainly of 16 toroidal field (TF) coils and 14 Poloidal Field (PF) coils. 13 Pairs of HTS (high-temperature superconducting) current leads are used for all the EAST SC coils, 13 pairs of SC feeders are used to connect each current lead with some coil[2]. In order to realize long-pulse steady discharging operation of the device, each SC coil is made by NbTi-based cable-in-conduit conductors (CICC) and cooled by forced-flow supercritical He[3] circulating through cooling pipe.

Long cooling-down process is required before the EAST operation because superconductor should run under the super-cryogenic condition at liquid He temperature. One of the key points for the EAST fusion device to realize the presetting physical goals is to cool down the SC magnet to work temperature at no more than 4.2K and keep long-term steady operation. Temperatures of different positions in the SC magnet system change unequally due to varied thermal loads during operation, while the resulting hot-spot temperature and uneven thermal distribution will degrade performance stablility of the whole SC magnet system. During both warm-up and cool-down, special attentions should be paid to control temperature difference between each coil inlet and outlet, keep reasonable temperature changing rate and maintain synchronous temperature variation between each group of coils[4]. Meanwhile, in the long-pulse steady discharging experiments, it is important for operational safety of the SC magnet system and reasonable discharging rhythm that A.C. (abbr. alternating current) loss of the SC magnet system should be calculated in time according to the coils' state parameters such as the inlet and outlet temperatures. Therefore, in the EAST SC magnet system 160 thermometers are installed to measure temperature on He cooling pipes, 78 of which are mounted on some key temperature measuring positions. Thermometer disposition is basically on the inlets and outlets of He cooling pipes of the SC magnet system as shown in Fig. 1. Measuring accuracy at He temperature is 100mK according to engineering operational requirements of the EAST tokamak[5].

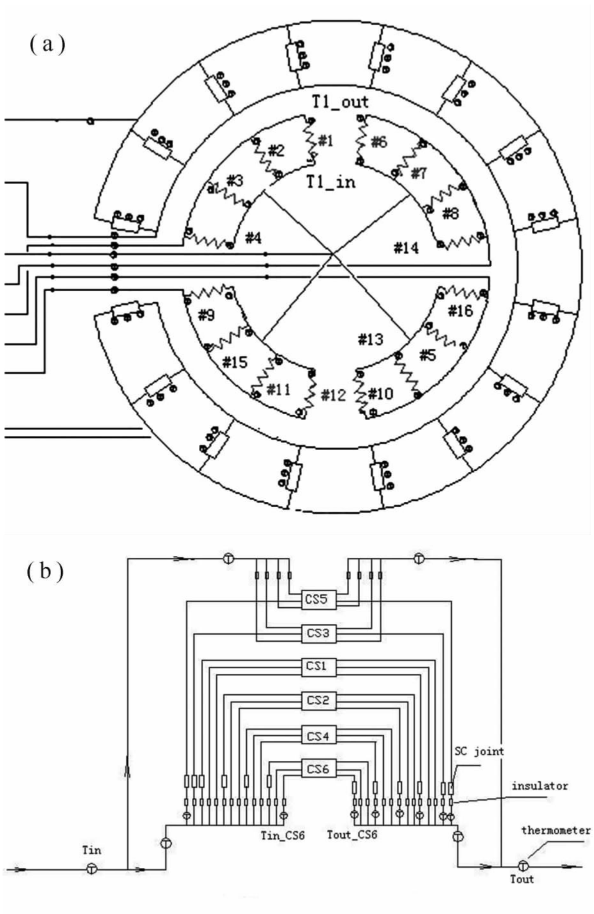

Fig. 1 (a) Location of Thermometers in TF coils
(b) Location of Thermometers in CS coils

2 MEASURING METHODS OF TEMPERATURE ON HE PIPES IN THE EAST SC MAGNET SYSTEM

2.1 Types and Installation of Thermometer on He pipe

Cernox-1050-AA, a type of resistance thermometer with negative temperature coefficient produced by Lakeshore, is adopted to measure temperature on He cooling pipe of the EAST SC magnet system. As a dedicated sensor for temperature measurement in strong magnetic environment, its main characters are listed as follows[6]:

(1) Temperature range of 100 mK (abbr. milli-Kelvin degree) to 420 K (model dependent).

(2) High sensitivity at low temperatures and good sensitivity over a broad range.

(3) Excellent resistance to ionizing radiation.

(4) Fast thermal response times: 1.5 ms (abbr. milli-second) at 4.2 K, 50 ms at 77 K.

(5) Excellent stability.

(6) Low magnetic field-induced errors.

Strict thermometer installation according to installation specifications is the precondition to ensure precise temperature measurement. To guarantee good thermal contact and avoid temperature gradient between cylindrical copper canned thermometer and cylindrical surface of He pipe being measured, a copper mounting substrate as shown in Fig. 2 is specially made whose size matches the pipe. The arc surface of the mounting substrate is direct soldered with sliver-copper bragging alloy to the stainless surface of He pipe. So the substrate acts also as thermal anchor between thermometer and the pipe surface. On the other hand, the mounting substrate should also establish good thermal contact with the thermometer for both good thermal conductivity and support. And there cannot be any clamp pressure that could damage thermometer. The cylindrical sensor surrounded with a thin layer of thermal vacuum grease must be fully inserted into cylindrical hole in the copper substrate marked *M*5 in Fig. 2. There is a brass screw at *M*5 which holds the bottom of the sensor lest it falls off. In the end the mounting substrate should be wrapped with layers of foils to get rid of varied radiation. Moreover, keeping the parts and mounting position clean and dry is necessary to prevent possible corrosion during installation.

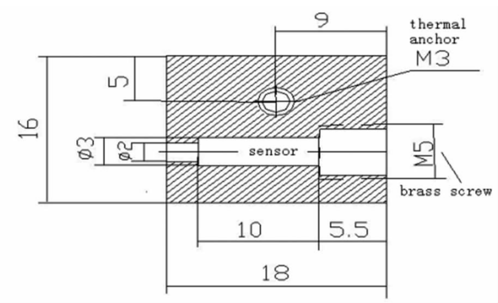

Fig. 2 Mounting substrate of Cernox-1050-AA thermometer

2.2 Measuring leads of Thermometer on He pipe

Standard four-lead method is applied to measure temperature on He pipe in the EAST SC magnet which can minimize effect of measuring lines resistance and contact resistance. Twisted wires are used as current leads and voltage leads for it can reduce noise. Measuring leads of temperature sensors on He pipe can be divided to 4 sections as shown in Fig. 3.

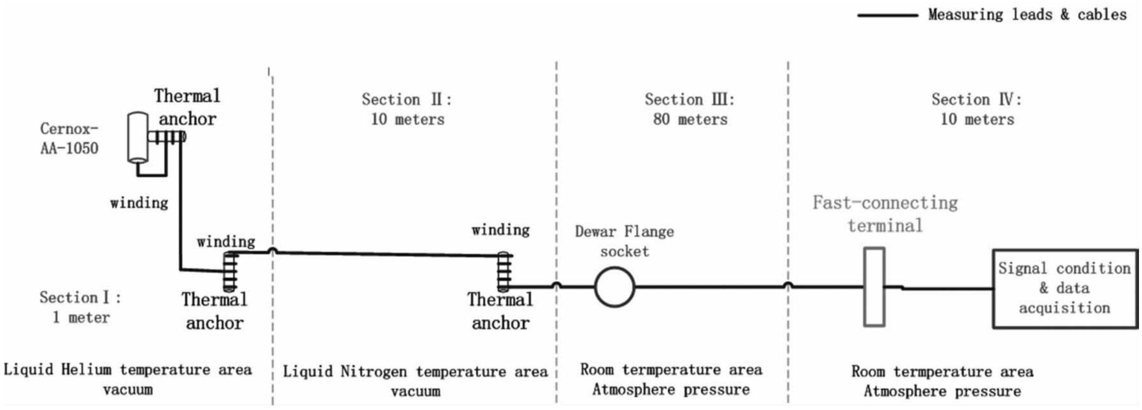

Fig. 3　Wiring layout of measuring leads of thermometer on He pipe ofEAST SC magnet system

The first section includes 4 teflon-wrapped Phosphor-bronze measuring leads about 15 centimeters in length whose one end are soldered to the two welding spots on the sensor chip. A spool-shaped copper thermal anchor, specially made for the measuring leads, is fixed with a brass screw to the thermometer at the position marked *M*3 in Fig. 2. Thus the special thermal anchor for measuring leads, copper mounting substrate, the stainless pipe surface being measured and the thermometer are combined to an isothermal body. Measuring leads should be wound around the special thermal anchor at least 5 circles before they are welded to the sensor to remove possible environmental ther mal that may conduct to the thermometer through the leads.

The second section is multi-core silver-plated copper leads insulated by polythene whose one end is welded to the Phosphor-bronze measuring leads ahead. And the other end of the leads is soldered to the inner socket of the EAST dewar flange. The leads in the section have high conductivity of thermal and electricity. The leads are laid across liquid He temperature area and liquid Nitrogen temperature area in the EAST device. Therefore, the leads should be wound at least 5 circles around the inner parts such as stainless pipe in the temperature changing area which can act as thermal anchor. Several layers of foil should be lapped around the leads and the thermal anchor to prevent thermal radiation and to fasten the leads.

The third section is multi-core shielded pair-twisted cable about 80 meters in length. One end of the cable is welded to the outside socket of the EAST dewar flange, while the other end is plugged to fast-connecting terminals and is wired from the site to the control room through stainless case. The fourth section is double-core shielded pair-twisted cable about 15 meters in length, which transfers signals from fast-connecting terminals to the BNC (abbr. Bayonet Nut Connector) in the signal conditioning units. In the whole path measuring leads should avoid any stress particularly when being wound around the specially made thermal anchor for the sensor.

2.3 Signal-conditioning and data acquisition of temperature on He pipe

Temperature ranges from 3.5K to 325K of thermometer for He pipe temperature of the EAST SC magnet, while the corresponding resistance value is from 40Ω to 8000Ω. Signal-condition unit including direct-current excitation source, differential amplifier, low pass filter and isolation part can change weak voltage signal from the sensor to signal suitable for analog input range of the data acquisition card[7]. Instrumentation flowchart of temperature measurement on He pipe is shown in Fig. 4.

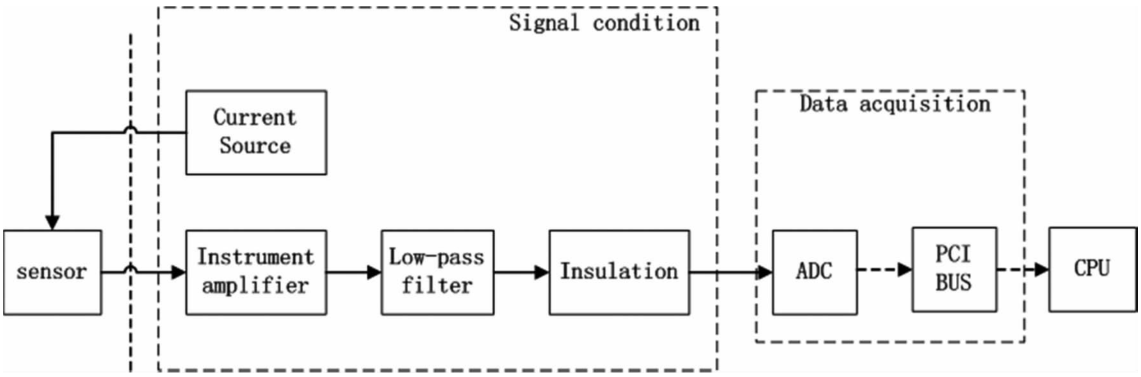

Fig. 4 Instrumentation flowchart of temperature measurement on He pipe

Ultra-precise constant current source parts with very low temperature coefficient and excellent stability are used in the direct-current excitation source. Constant current amplitude output from the excitation source is 10uA with accuracy of about 0.3% to prevent thermometer self-heating and to be operated conveniently. Thus voltage amplitude output from the thermometer is weak ranging from 400uV to 80mV. It is primary that noise factor of the first stage amplifier circuit should be small enough in any weak signal measurement system[8]. Differential instrument amplifier with low noise and low distortion and high common mode rejection ratio is selected as preamplifier in the signal conditioning unit. Its differential input impedance is 60MΩ||2pF far bigger than that of the signal being tested, which greatly reduces common mode noise of the input signal. Thermal response rate of thermometer is no more than 3Hz in the measuring temperature range. So the cutoff frequency is set at 13Hz of low-pass filter in the signal condition unit. For effective noise suppression a fourth order Butterworth low-pass active filter is made up of two second order filters composed of several operational amplifiers OP07 and precision non-inductive metal film resistors and capacitors, which provides the unit with steep amplitude-frequency characteristic in the vicinity of the cutoff frequency. The gain is 100 to match ±10V analog input range of the data acquisition card with 16 bit precision. Therefore voltage amplitude is from 40mV to 8V of the input signal to the data acquisition card. High linearity analog optical coupler is also used to realize electric isolation between signal condition units and data acquisition card. Meanwhile it can help remove common mode noise in the circuit. Electrical equipments in the measurement system are powered by an independent double online UPS system for operational steadiness and safety.

3 ERROR SOURCES AND EFFECTS OF TEMPERATURE MEASUREMENT ON He PIPE

Error sources of temperature measurement on He pipe of the EAST SC magnet system include thermometer calibration error, thermometer resistance-temperature ($R\sim T$) fitting error, thermometer installation error, measuring lines related error and error of signal-conditioning and data acquisition.

3.1 Errors caused by sensor calibration, fitting and installation

Each thermometer has its individual $R\sim T$ characteristic curve. All the thermometers on He pipe of the EAST SC magnet system were calibrated to get their own $R\sim T$ characteristic curves and fitting coefficients of three-dimensional 12th order Chebychev polynomial used for $R\sim T$ numerical conversion. Thermometer calibration accuracy can reach mK level in liquid Helium temperature zone (that is from 4.2K to 25K) and 10 mK level in liquid Nitrogen temperature zone (that is from 25K to 280K). $R \sim T$ numerical fitting error is within 10mK level in liquid Helium temperature zone. For all the thermometers being used were installed in strict accordance with the manufacture's installation specification, error caused by installation is considered negligible.

3.2 Errors caused by measuring leads

Each thermometer for temperature on He pipe of theEAST SC magnet system has two current leads and two voltage leads. Each lead is about 100 meters in length and its resistance is about 5Ω. Due to the four-lead measuring method the lead resistance and contact resistance between the lead and the connections can be ignored. Voltage lead in cryogenic temperature area is floating pair-twisted silver-coated manganin lead. And weak voltage signals in room temperature area transfer through multi-core shielded cable about 80 meters in length. The shielding copper net of the cable is single-end grounded at the fast-connecting terminal to break circuit loop in order to prevent possible interference current flowing through the copper shielding net from coupling to the weak thermometer signal. To minimize thermal emf (abbr. electromotive force) a voltage lead in the four measuring leads should be a single lead throughout, which means no joints existing in the whole wiring path[9]. However, there are 3 welding spot joints and a fast-connecting terminal joint along a voltage lead, which is certain to cause some error. Error caused by welding spot joints is ignored because welding spot joints are tiny and with smooth and clean surface and leads near welding spots have necessary thermal anchor treatment. Differential temperature potential resistance is no more than 1.8mΩ of fast-connecting terminals. Error caused by thermal emf is about 10mK in room temperature and negligible in liquid He temperature.

3.3 Errors caused by signal-conditioning and data acquisition

Signal-conditioning unit in the He pipe temperature measurement system of the EAST SC magnet system has zero and gain adjustment. The two functions can effectively remove offset and gain error of the chips, but not get rid of nonlinear error of amplifier, which is no more than 24mΩ in room temperature and 4.8Ω in liquid He temperature. Error caused by high linearity optical coupler as electric insulator is no more than 24nΩ in room temperature and 5Ω in liquid He temperature. Measuring error from 16-bit precision data acquisition card and its signal transmission unit is no more than 1mV, and its corresponding thermometer resistance is about 1Ω. Error from constant current excitation is about 100mK in room temperature and 1mK in liquid He temperature. The data acquisition frequency is 100 Hz. Median average filtering method is applied in software process to remove error caused by pulse interference. It is concluded that overall error in the signal-conditioning and data acquisition process is no more than 6Ωin room temperature and 11Ω in liquid He temperature.

3.4 System error and working result of temperature measurement on He cooling pipe

During cool down and warm up process temperature on He pipe of the EAST SC magnet system changes from room temperature to liquid helium temperature. Primary temperature control lies in temperature difference between the pipe inlet and outlet of each coil, keeping uniform and synchrony and reasonable temperature changing rate. Thus it is required that the measuring error is no more than 10K during the two processes. During plasma discharging operation it is required that the measuring error is below 100mK for stability analysis such as the SC magnet thermal load calculation and performance judgment like whether temperature on some position exceeds presetting threshold. Summing up all the error sources in temperature measurement on He pipe of the EAST SC magnet system, the measuring error is no more than 6K in room temperature and 30mK in liquid helium temperature, which meets the engineering requirements. Real-time temperature data on He pipe inlet and outlet of the TF magnet system is shown in Fig. 5

during cool down in the EAST spring campaign in 2012. Temperature difference between the inlet and outlet of He pipe of each coil is no more than 8K. Temperature difference of all the outlets is no more than 12K. And temperature difference of all the inlets and outlets of different coils is no more than 50K. All the data show that temperature control of the SC magnet system meet the engineering requirements.

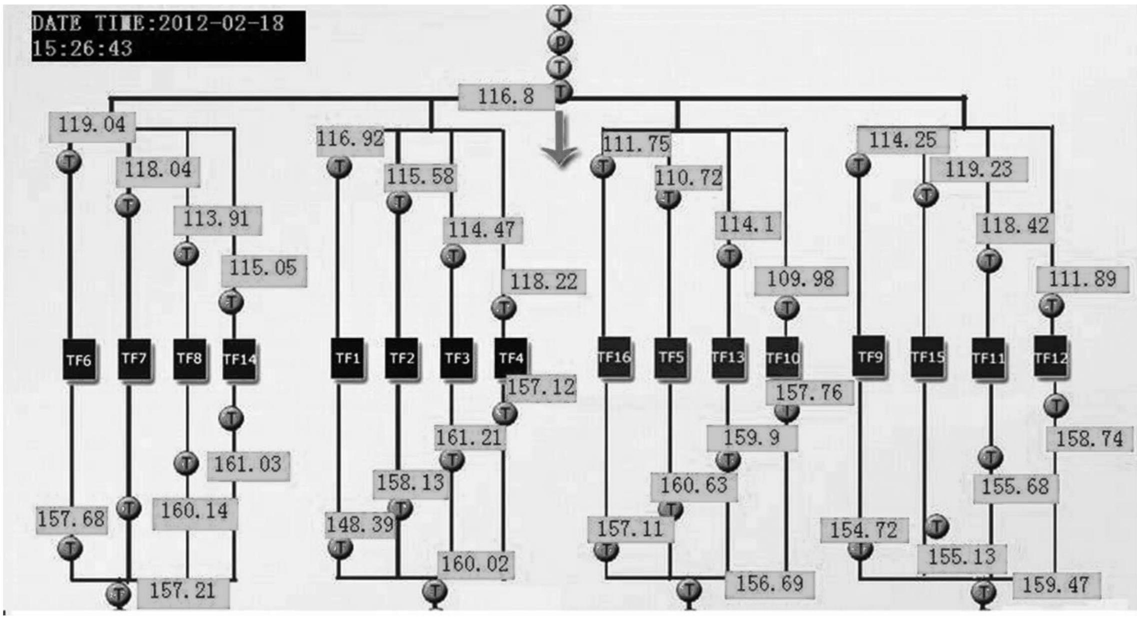

Fig. 5 Inlet and outlet temperatures on He pipes of the TF magnet system during cool down

4 CONCLUSION

Cryogenic SC magnet has broad application in nuclear fusion research, large capacity energy storing device, SC electric generator and synchrotron and etc.[10]. Precise temperature measurement of the SC magnet is important for SC magnet state monitoring and operational safety. More attention should be paid to temperature measurement methods and error sources elimination, especially in large-scaled SC magnet systems which plan to run steadily for dozens of years.

The EAST SC magnet system has gone through eight cool down experiments and seven plasma discharging experiments since 2006. Although temperature measurement on He pipe of the SC magnet system meets the engineering requirements, four factors as followed can further improve measuring accuracy and stability.

4.1 Best installation location selection for the sensor. Temperature at the location should reflect

cryogenic cooling procedure. For future comparative analysis of the sensor data of similar locations, distance between the sensor and the relative valve and location at the circle of the cooling pipe should also keep consistent.

4.2 Best sensor type selection according to temperature measuring range and its corresponding

resistance range, thermal response rate, physical size and installation technology and other characteristics of the sensor. At the present with cost reduction and installation technology development, SD type of Cernox sensor is broadly applied in quite a few large-scaled SC magnets like the KSTAR device in South Korea, whose advantages are listed as below.

- Fast thermal response rate (24 times faster than that of AA type sensor in the EAST device)
- Small physical size (two third of width and one third of length and height of AA type sensor)
- No need of copper mounting substrate which can also act as thermal anchor

4.3 The combination of programmable signal process unit and software data process can realize online auto-zeroing and get real-time gain

By current excitation amplitude adjustment according to real-time thermometer resistance value, thermometer self-heating could be minimized while its voltage output could be relatively maximize. Data is more accurately calculated with real-time channel parameters such as gain and current magnitude and etc. during software data process.

4.4 The nearest measurement principle

The distance from thermometers on He pipe to the measuring units is about 100 meters. In theory measuring lead resistance and related contact resistance can be ignored with the four-lead method. In fact there exists some line loss after years of operation which can cause voltage attenuation of about 10μV. In liquid He temperature, measuring error from the attenuation is at mK level which can be ignored. However, measuring error from the attenuation is about 5K in room temperature. To minimize possible measuring error caused by aging cable, signal process and acquisition units should be placed as near as possible to the sensors if allowed. And optical fiber can be used for long distance signal transmission.

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EAST 超导磁体系统液氦温度测量方法与误差分析

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【摘要】　在 EAST 托卡马克核聚变实验装置中，超导磁体系统的热负荷计算、超导性能和及其运行稳定性都与运行温度有很大关系，因而要求液氦温度测量有较高测量精度．文中主要讨论 EAST 超导磁体系统中液氦温度测量的相关技术、误差来源及其影响，同时提出一系列减小误差的方法，取得了较好的实验运行结果，满足了工程要求．这些方法对低温微弱信号测量具有普遍适用性．

关键词：EAST 超导磁体系统，液氦温度测量，误差来源

PACC： 0720，0750

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