LOW TEMPERATURE INSTRUMENTATION FOR SUPERCONDUCTING ACCELERATORS

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Abstract

The report presents the R&D program covering the problems of precise control of the sate of two-phase helium flow and multipoint temperature measurement in cryogenic system of a superconducting accelerator.

1 INTRODUCTION

As acknowledged recently, to achieve the ultimate performance of an accelerator it is necessary to control accurately the state of a cryogen. For instance, at Tevatron [1], the stratification of two-phase helium flow in dipoles reduces the attainable energy; at TESLA [2], the smooth cooldown procedure (controlled mixing of gaseous and liquid He) is necessary to prevent mechanical problems in the TTF structures. So, while employing the two-phase coolant, one has to monitor the void fraction besides the temperature and pressure of a flow. Next issue is the temperature measurement in the numerous of locations over the cold mass. It requires a multitude of sensors operating under irradiation and corresponding wiring which has to be simplified with the use of multiplexers.

A progress is achieved at JINR on the above mentioned problems and the results are presented below. Design, calibration technique and working characteristics of the void fraction transducers (RF sensors of dielectric permittivity of helium flow) are described. Tests of cryogenic thermometers and analog multiplexers under fast neutron and gamma irradiation at 77 K are reported. Modular multichannel measuring system capable to manage the resonant void fraction sensors, resistance thermometers, pressure gauges and other sources of analog signals is presented.

2 VOID FRACTION

Since helium is dielectric, it is rather convenient to employ a sensor responding to the mean dielectric permittivity of media ε:

$$\varepsilon \approx \varepsilon_g \cdot \varphi + \varepsilon_l \cdot (1 - \varphi) ,$$

where ε_g and ε_l are the dielectric permittivities of gas and liquid phases, respectively. One can determine the thermodynamic state both for the two-phase and single phase dielectric flow with the values of ε and pressure P (what is impossible with the traditional ‘temperature-entropy’ diagram). It is necessary to note, that the measurement accuracy is of principal importance because of the minor difference of ε_g and ε_l values. For example, in the case of helium

$$(\varepsilon_g - \varepsilon_l)/ \varepsilon_l \approx 4\%.$$

Thus, the error of ε measurement must be at least two orders of magnitude smaller - 0.04%.

2.1 Measurement Principle

High accuracy is achieved by using the radio frequency method. This method involves a signal capacitor connected to an oscillatory circuit whose resonant frequency, f, depends on the void fraction φ of the fluid filling the measuring volume.

2.2 Sensor Design

The cross section of the typical sensor follows the geometry of the helium flow channel in an accelerator and is either round or annular.

For an annular channel the void fraction sensor is made as the short-circuited coaxial lines connected to the measuring gap. The narrower the gap, the higher sensitivity, because of the sensitivity, $1/f \cdot df/d\varphi$, is limited by the electric field nonuniformity [3].

For a round channel the high uniformity of the filed in the measuring volume is achieved by the excitation of the first mode resonance in a meander line formed on the dielectric tube surface [3].

The construction details alters from one specific design to another. Typical characteristics of the round-cross section sensor of 70 mm inner diameter are as follows: resonant frequency - 40 MHz, signal range - 100 kHz (Δf with φ=0…1), quality - 300 (liquid He @ 4.2 K).

2.3 Calibration Technique

The feature of the used technique is that the calibration of an RF sensor is performed on the experimental data obtained under conditions of He equilibrium state which can be reproduced with the high degree of authenticity.

The resonant frequency of a sensor is determined as $f=1/[2\pi\,(L_{eff}\,C_{eff})^{1/2}]$, where L_{eff} and C_{eff} are the effective values of the sensor inductance and capacitance. Calibration characteristic of the sensor is [3]

φ = **Error!**.

The constants $K_3=K(\varepsilon_c)$, K_1 and K_2 are determined during the calibration. The general form of expression for φ is $\varphi=\varphi(f,\ \varepsilon_l,\ \varepsilon_g,\ f_1,\ f_2,\ \varepsilon_1,\ \varepsilon_2)$ where, in the case of a vapor-liquid flow, ε_l and ε_g are determined by the current value

P of pressure; $\varepsilon_1=\varepsilon_{0l}$ and $\varepsilon_2=\varepsilon_{0g}$ - by the value P_{0s} of pressure at which the calibration was carried out. So, in many cases $\varphi=\varphi\ (f,\ P,\ f_{0l},\ f_{0g},\ P_{0s})$ and five quantities will be the input parameters to the intellectual part of the measuring device. The values f and P (or temperature) are measured and the f_{0l}, f_{0g}, P_{0s} are taken as the reference parameters.

2.4 Measuring System

The structural scheme of the radio frequency channel with the usage of the tracking feedback was described elsewhere [3]. To determine the resonant frequency, the sweep generator sends a signal to the sensor. From the sensor the frequency signal goes to the extreme regulator which controls the sweep generator and maintains the resonant frequency. The RF sensor is connected with the measuring board through the removed detector which contains the input preamplifier, detector, and buffer amplifiers to ensure its operation with a comparatively long cable (up to 30 m). A merit of this way is that it allows one to measure the resonant frequency of the sensor directly, and the reliability of measurements depends on the accuracy of the sensor mainly.

The main parameters are as follows: measured resonant frequency can be regulated within the range of 5 MHz to 50 MHz, accuracy of measurement is about ≤500 Hz at helium temperatures, time of a measurement is about 100 ms, interval between measurements - 1 s.

The total error $\delta\varphi$ at 4.2 K (including the instrumental error, temperature- and pressure-related uncertainties, and the calibration error) is less than 2%.

The Modular Industrial Computer MIC 2000 based on the ISA-bus and micro PC, is used to construct the measuring device. Usage of the cross-bus with several slots, allows one to enlarge the number of measurement channels and to add the complementary possibilities for other measurements, for example, temperatures, pressures, etc. There are two operation regimes: stand-alone and with the removed PC.

The developed software provides the following: the internal self-test of the device, calculation of the dielectric permittivity and void fraction of helium using the measured resonant frequency, calculation of the necessary parameters of helium via ε and T (or P) using the helium state equation, measurements of the temperature, reading the user input from the keyboard and GPIB or Ethernet interface, displaying the results of measurements and calculations and/or sending the response to the removed computer.

3 THERMOMETRY

The following types of cryogenic resistance thermometers suitable for employing at an accelerator, have been thoroughly tested: rhodium-iron RIRT, platinum PRT, carbon-glass CRT, and carbon TVO resistor. The RIRT, PRT and CRT sensors are produced and calibrated by VNIIFTRI (National Standard Institution, Moscow, Russia) and their characteristics are well known and available from the manufacturer. The data on TVO are scattered, e.g. see [4], and so they are presented in details in the next section.

3.1 TVO Specifications

Typical characteristics of the TVO thermometers are:

- Materials: carbon powder 50...200 Angstrom (about 4%), the rest components are the boron/lead flux and corundum powder (ceramics).
- Nominal value: 910 or 1000 Ohm @ 300 K.
- Calibration characteristic:

T, K	2	4	20	77	300	400
R, Ohm	7100	3600	1900	1400	1000	950

- Sensitivity:

T, K	2	4	20	77	300	400
dR/dT, Ohm/K	3000	500	27	4	0.8	0.5

- Stability: the error increases during 7 years

T, K	4	77	300
Error, %	0.4	0.9	0.9

- Configuration: rectangular prism of 8×2.4×1.3 mm^3 with two leads.
- Magnetic field effect: $\Delta T=2.\cdot10^{-6}\cdot dR/dT\cdot B^2$, where dR/dT corresponds to 4.2 K and B is the magnetic induction, Tesla. Orientation of the sensor in the magnetic field practically does not influence upon the readout. Usually the value $\Delta T/T$ is less than 1% for the induction up to B=5 T [4].

3.2. Radiation Performance Tests

The experiment was arranged at the Pulse Reactor IBR-2, Laboratory of Neutron Physics of JINR [5]. It produces a full spectrum of fast neutrons ranging from about 10^{-1} to 20 MeV; average energy, E_n, is about 1 MeV. The reactor can deliver the neutron flux up to 10^{12} cm$^{-2}\cdot$s^{-1} over areas up to 20×40 cm^2. In addition to the neutron, the gamma radiation is also produced in the nuclear reactions with maximal dose rates up to 10 Gy·s^{-1}: the average energy is of about $E_\gamma \approx$1.5 MeV. The ratio between the neutron fluence and the gamma dose can be varied by several orders of magnitude by means of the appropriate beam filter and absorbers. The flux of fast neutrons of about 10^{10} cm$^{-2}\cdot$s^{-1} was used for our measurements. The experimental setup includes a cryostat for the sensors, a beam filter, boron carbide layer, movable shielding platform, beam shutter, inner and outer reactor shields, cryogenic lines, measurement cables, nickel foil for both - monitoring of the total power and measuring the homogeneity of the neutron fluence. The accuracy in determining the fluence of the fast neutrons and γ-dose was ±10%. The data, temperature shift ΔT due to irradiation, listed in Tab.1 are obtained for irradiation at 77 K earlier [5] and recently.

Table 1: Radiation resistance of temperature sensors.

Thermometer	Fluence, cm^{-2}	γ dose, kGy	ΔT, mK
Rh/Fe, RIRT-2	$7 \cdot 10^{15}$	90	18
Pt, PRT-5V	$7 \cdot 10^{15}$	90	10
Carbon, TVO	$2.4 \cdot 10^{14}$	100	25
Carbon, TVO	$5 \cdot 10^{15}$	22	50
C-Glass CRT-2	$5 \cdot 10^{15}$	80	10

3.3. Multiplexer

The aim of using the multiplexer is to reduce significantly the number of leads entering the cryostat. It is achieved with two high-speed 16-channel CMOS-multiplexers of PC74HC/HCT4067 type. These chips are placed within the helium vessel and switch the potential wires from one sensor to another. In result, only 7 wires are used instead of 34 to measure the four-lead resistance of 16 sensors connected in series.

The tests of the MUX board have been performed under the radiation environment conditions. The parameters were: temperature in cryostat 77 K; neutron fluence $3.7 \cdot 10^{8}\,cm^{-2} \cdot s^{-1}$; gamma dose rate 400 Gy·hour. The following characteristics of the chip were measured: the resistance of the open channel - R_{on}, matching of the channel resistances - ΔR_{on}, the dynamic current of supply - I_{supp}. The data are listed in Tab.2 and show that the main characteristics become worse gradually with the increase of dose. A sudden failure of the multiplexer occurred at the total dose of about $4.8 \cdot 10^{13}$ cm^{-2} + 14.5 kGy.

Table 2: Radiation performance of MUX

Gamma dose, Gy	0	$0.4 \cdot 10^{4}$	$1.4 \cdot 10^{4}$	$1.45 \cdot 10^{4}$
Neutron fluence, cm^{-2}	0	$1.3 \cdot 10^{13}$	$4.6 \cdot 10^{13}$	$4.8 \cdot 10^{13}$
R_{on}, Ohm	35...40	56...62	80...110	-
ΔR_{on}, Ohm	5	6	30	-
I_{supp} (@ 5 kHz), mA	3	5	80	150

The more detailed information on the behavior of the different MUX chips, including the data on the leakage currents I_{leak} will be published soon.

3.4. Temperature Measurement System

The system realizes the DC current four-wire method for resistance measurement with inversion of excitation current. It is designed as a set of modules for the MIC2000 industrial PC (see sec. 2.4 above) and includes the following units:

- three precise current sources (one fixed and two programmable) covering the range from 1 μA to 2 mA;
- two analog to digital converters: integrating 18 bit ADC and fast 12 bit ADC;
- three matrix switches for current sources, ADCs, and sample resistances;
- scanner for 512 analog input channels;
- signal conditioning board;
- board to control the 74HC4067 cold multiplexers.

The system allows the temperature resolution of a few milli Kelvin @ 4.2 K with the TVO thermometers and scanning over tens of sensors in a few seconds.

10 CONCLUSION

The designed and tested RF void fraction sensors and measuring device are reliable, and provide a comparatively high accuracy (error $\delta\varphi$ is less 2% for void fraction) while measuring the characteristics of two-phase helium flow. The calibration procedures are simple enough and based on the experimental data obtained under condition of cryogen equilibrium states only.

The accuracy of temperature measurement over the cryogenic temperature range is 10, 50, and 100 mK at 1.5, 77, and 300 K respectively. All the tested thermometers: RIRT, PRT, CRT, and TVO exhibit stable performance under irradiation. With the neutron fluence plus gamma dose up to $7 \cdot 10^{15}\,cm^{-2}$ + 90...100 kGy, the deviations are close to the calibration uncertainty.

Multiplexer 74HC4067 can be used in the environment combining the fast neutron and gamma radiation up to $(1.3...4.6) \cdot 10^{13}\,cm^{-2}$ + 10 kGy at 77.4 K. Further tests are necessary of the leakage currents I_{leak} behavior.

The modular-PC based measurement system manages two channels for φ-sensors, 512 channels for T and P sensors and allows further extensions.

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