Cs-He OPTICALLY PUMPED MAGNETOMETER - THE REFERENCE GAUGE OF MAGNETIC INDUCTION FOR NATIONAL METROLOGICAL CENTRES

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ABSTRACT

This paper presents the results of improvement and manufacture of prototype models of the Cs-He converters for precise magnetic measurements and *development of a new type* of a *Cs-He magnetometer* for metrological purposes to be used as a standard measuring device.
The MQCH-03 Cs-He magnetometer has been tested in accordance with requirements imposed by metrological application and has the highest absolute accuracy. Such an approach to the design of a Cs-He magnetometer resulted in an instrument *with unique metrological characteristics.* The majority of the National Metrological Centres and leading foreign firms (Sintrex, Gem Systems – *CANADA* ; Geometrics – *USA*) producing magnetometers *have no* similar reference Cs-He converters and magnetometers.

magnetometer, optical pumping, Cs-He, magnetic induction, reference

1. INTRODUCTION

Among magnetometers with optical pumping the magnetometer on ^{4}He atoms in the metastable 2^3S_1 state occupies a special place. Magnetometers on ^{4}He are made using the M_z - signal circuit with frequency lock to the resonant frequency ω_0 of ^{4}He atoms and have a slower response in comparison with M_x - magnetometers based on alkaline metal atoms. However, the ^{4}He atom has a number of the attractive features: the highest gyromagnetic ratio (conversion factor), $\gamma/2\pi \approx 28$ Hz/nT; the high signal/noise ratio; the principally linear dependence of the resonance frequency on the magnetic induction, $\omega_0 = \gamma \cdot B_0$; the spin-system of ^{4}He atoms has a simple and equidistant structure of Zeeman levels, $m_F = 0, \pm 1$; and, finally, the ^{4}He atomic gas, as the working substance, does not require of thermostabilization which is its major advantage in magnetic field measurements in extreme conditions.

At conventional (direct) optical pumping of ^{4}He atoms, the absolute error due to the sensor space orientation can amount 2÷3 nT, whereas its sensitivity is $\sim (1 \div 2) \cdot 10^{-2}$ nT. The distinction of these parameters is caused by the shift of a magnetic resonance frequency ω_0 due to direct action of an intensive pumping light of a helium lamp [Ref. 1].

Two groups of the Russian researchers have offered different ways of improvement of ^{4}He optical pumping process with the aim to reduce a systematic (orientation) error.
The members of one group (S.I.Vavilov Optical Institute, St. Petersburg) have modified the process of direct optical pumping of ^{4}He atoms and have shown a possibility to decrease a systematic error by an order of magnitude and more [Ref. 2].
The members of the other group (A.F.Ioffe Phys.-Technical Inst., RAS) have offered an indirect pumping process of ^{4}He at which the direct action of light on ^{4}He atoms was eliminated [Refs 3, 4]. They suggest pump other atoms (for example, cesium), which then transfer the moment to ^{4}He atoms by a spin exchange. The absorption cell, in this case, contains both ^{133}Cs and ^{4}He atoms. This idea has proved to be the most fruitful for practical realization of the high potentialities of a resonance in ^{4}He. The experimental prototypes of the alkaline-helium ″induction-to-frequency″ converters of the highest accuracy were made. In particular, on the basis of Cs-He converters, the A.F.Ioffe PTI, RAS, in cooperation with the D.I.Mendeleyev VNIIM, have developed a quantum current standard [Ref. 5] within a range of (0.1÷1 A) with an extremely low standard deviation of $2 \cdot 10^{-8}$ at a current of 1 A. Further, the Cs-He converter was used to refine the physical constants [Ref. 6].
On the basis of results of development of experimental prototypes of Cs-He converters the GNPP ″Geologorazvedka″ (Research & Production Enterprise, St. Petersburg) began production engineering of these converters in 1995.

This paper presents the results of work in the following directions:
- *improvement and manufacture* of prototype models of the Cs-He converters for precise magnetic measurements;
- *development of a new type* of a *Cs-He magnetometer* for metrological purposes to be used as a standard measuring device [Ref.7].

2. Cs-He CONVERTERS

We have made a substantial amount of work on the engineering documentation, provided by the VNIIM Institute, and manufactured new developmental prototypes of Cs-He converters. After adjustment and tests these devices had better accuracy parameters than all other gauges of magnetic induction known in the metrology.

2.1 Block diagram of a measuring system (Fig. 1)

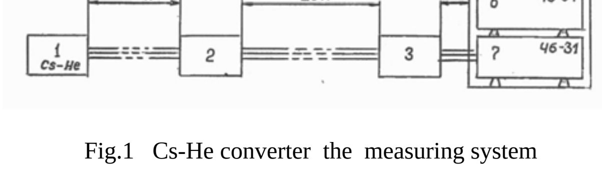

Fig.1 Cs-He converter the measuring system

Magnetic sensor unit - *sensor* (1), made with a high degree of magnetic cleanness. A high degree of magnetic cleanness of the sensor was achieved due to development of a *technological cesium gradiometer* which allowed to carry out

detection of a very weak magnetic contamination of non-magnetic materials and components of the sensor. *The gradiometer had a sensitivity of* ~ 0.002 nT (~ $2 \cdot 10^{-12}$ T). The *residual magnetization* of the Cs-He *sensor* was reduced to a level of ≤ 0.01 nT.
The electronics unit (2) also has a high non-magnetic properties and is removed from the Cs-He sensor by 4 m *The synchronous detector* (3) and a *rack* (4) with *standard instrumentation* are removed from the sensor (1) approximately by **25 m** (5 – oscillograph, 6 – frequency counter, 7 – frequency synthesizer).

2.2 Investigation results

The investigations of the optical pumping process, carried out at the enterprise, have led us to understanding of a *physical nature of the systematic (orientation) error* which amounts to ~ 0.07 nT. As a result, the *systematic measurement error* of **Cs-He converters** was reduced down to **≤ 0.03 nT**.

We have carried out an *optimization of the electronic circuits*, in particular of the component parts of the pulse high-frequency discharge for the Cs-He absorption cell and of the photodetector device of the sensor signal. This resulted in reduction of a *random error*, **σ ≤ 0.003 nT**. The example of time stability of the measuring system of Fig.1, is shown in Fig. 2.

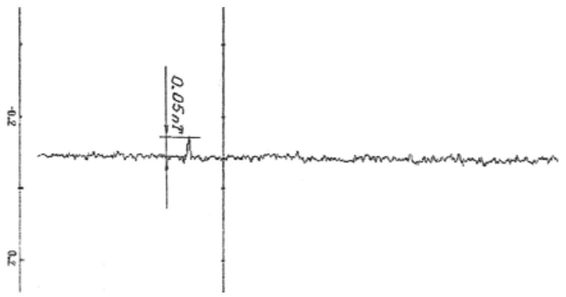

Fig.2 Recorder trace of time stability of the measuring system

In 1995 these measuring systems *were installed* at the National Metrological Centres of Russia (VNIIM), Republic of Korea (KRISS), and also at the 1-st category calibration setup of the "Geologorazvedka" Enterprise, and now reliably work.

3. Cs-He MAGNETOMETER

On the basis of the improved Cs-He converters a new original *Cs*-He a t omsina sish ***MQCH-03*** was designed as a standard measuring device. It consists of two units: the *Cs*-He *sensor* (1) and *electronics unit* (2), Fig. 3.

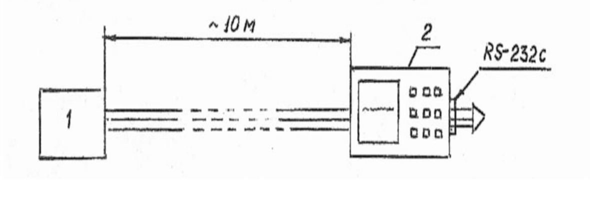

Fig. 3 MQCH-03 block diagram

The block (2) is placed *10 m* away from Cs-He sensor (1) and is made completely of foreign-made components by "Analog Device" and "Motorola". It should be noted that the block (2) of magnetometer performs all functions of blocks (2), (3) and instrumentation rack (4) of the measuring system Fig. 1.
The block (2) of the magnetometer is software controlled *microprocessor system* and provides an automatic search and a lock to a magnetic resonance frequency of the ^{4}He atoms, functioning of the analog-digital system of tracking of field changes, digital display of measurement results on the graphic display and other functions. It contains 7 main components: the terminal, radio frequency controller, graphic display, keypad, two high-frequency units and the power supply.
Some feature should be noted.

The frequency synthesizer in the terminal is an integral digital 32-bit frequency synthesizer. It works with clock frequency 20 MHz and has a quantization step ~ 0.005 Hz. The data on states of the components and units are shown on the graphic display. With the help of the *keypad* it is possible to set various parameters of work of the Cs-He sensor, for example, modulation frequency, quantization frequency step in searching resonance, etc. The measured field is displayed with 9 – digits, the least significant digit **~ 0.001 nT** (i.e. **1 pT**).
The device of control in the radio frequency controller is the single crystal processor with the RS-232 C interface at the unit output for the spectral processing of signal.

The MQCH-03 Cs-He magnetometer has been tested in accordance with requirements imposed by metrological application and has the highest absolute accuracy [Ref. 7]. A general view of the MQCH-03 are given in Fig. 4.
These investigations show the way to further improvements of the performance and metrological parameters of the reference magnetometers..

Fig. 4 MQCH-03 Cs-He magnetometer

Applications:

- Reference measuring equipment and magnetic field standards in magnetic observatories.
- Calibration and standardization of optically pumped, proton precession and fluxgate magnetometers for different applications (ground, airborne and spaceborne, marine, borehole).
- Investigations in basic theoretical metrology.

Specification of Cs-He magnetometer MQCH-03 :

- measurement range 1000 to 100 000 nT
- systematic measurement error including orientation error 10^{-4} %
- conversion factor A 28.023 814 Hz / nT
- root-mean-square derivation of random error component for integration time of is 0,01 nT max
- root-mean-square derivation of factor A $< 3{\cdot}10^{-7}$ Hz /nT
- permissible magnetic field gradient in the sensor absorption cell volume, max < 2 nT / cm
- max. tolerable rate of magnetic field variations 200 nT/ s
- operating temperature range 15^0 C to 35^0 C
- supply voltage 220 V, 50-60 Hz
- power consumption 15 W
- dimensions; weight : sensor 65 (DIA) x 240 mm; 1 kg
  console 350 x 150 x 290 mm; 5 kg
  connecting cable 10 mm

- provided with a LCD 320 x 200 DOT graphic display screen
- "RS-232C" interface
- The optically pumped sensor may be located at a distance of up to **10 m** from the console

4. CONCLUSIONS

Such an approach to the design of a Cs-He magnetometer resulted in an instrument *with unique metrological characteristics*, which make it highly competitive in the world market.
The majority of the National Metrological Centres and leading foreign firms (Sintrex, Gem Systems – *CANADA*; Geometrics – *USA*) producing magnetometers *have no* similar reference Cs-He converters and magnetometers.

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