Technical Physics, 2025, Vol. 70, No. 11

15

Magnetic field compensation system for Baksan large neutrino telescope

© A.D. Lukanov, A.A. Budzinskaya, D.M. Voronin, V.N. Gavrin, D.S. Gursky, T.V. Ibragimova, B.K. Lubsandorzhiev, S.B. Lubsandorzhiev, D.A. Nanzanov, A.Yu. Sidorenkov, N.A. Ushakov, A.N. Fazliakhmetov, A.A. Shikhin

Institute for Nuclear Research of Russian Academy of Sciences,
108840 Troitsk, Moscow, Russia
e-mail: arslanlukanov@yandex.ru

Received March 6, 2025
Revised June 4, 2025
Accepted June 9, 2025

A system for compensating the Earth's magnetic field, developed for the Baksan Large Neutrino Telescope, is presented. The system is based on the use of Helmholtz coils. The compensating magnetic field is generated within a cylinder 32 meters in height and 15.5 meters in radius. According to calculations, the residual magnetic field amounts to 0.05 G. The algorithm for calculating the magnetic induction generated by the coils is described. The main parameters of the coils are considered, and a calculation of conductor heating for the developed magnetic field compensation system is provided.

Keywords: Magnetic field, Helmholtz coils, Photomultiplier tubes, Neutrino detector.

DOI: 10.61011/TP.2025.11.62246.30-25

Introduction

The Baksan Large Neutrino Telescope (BLNT) is being developed at the Baksan Neutrino Observatory of the Institute of Nuclear Research of the Russian Academy of Sciences (BNR INR RAS) in the North Caucasus. The detector will be a complex structure with a three-zone structure. The central zone is supposed to be made in the form of an acrylic sphere with a radius of 14 m filled with a liquid scintillator based on linear alkylbenzene (LAB) weighing 10 kt. The buffer area surrounding the central zone will be filled with non-scintillating organic liquid to suppress the background from the detector materials, the outer zone of the detector will be filled with water [1].

At the moment, the first detector with a target mass of 0.5 tons has been put into operation and is fully functional. The detector design consists of two zones. The central zone is an acrylic sphere with an inner radius of 0.48 m filled with a liquid LAB-based scintillator. The sphere is viewed by twenty 10-inch Hamamatsu R7081-100 WA-S70 photomultipliers mounted on a steel frame around the sphere. The acrylic sphere is located in a polypropylene tank, which is filled with ultrapure water to protect against external radioactivity. The thickness of the water layer is 70 cm.

The second prototype detector with a target mass of 5 t is at the assembly stage. The detector also consists of two zones. An acrylic sphere filled with a liquid scintillator has a radius increased to 1.1 m. The height of the water tank is 4 m, radius is 2 m, thickness of the water layer is 0.9 m. The acrylic sphere scanned by forty-two 10-inch PMT Hamamatsu R7081-100 WA-S70. Also, twelve 8-inch PMT Hamamatsu R5912-100 WA-S70 used in the muon veto system were added to the detector design. A magnetic field compensation system using Helmholtz coils was developed for the prototype. 5 coils with ten turns each are used to compensate for the vertical component, 12 rings with seven turns were used to compensate for the horizontal component, the current in all coils is 2 A.

1. Magnetic field compensation methods

The values of the Earth's natural magnetic field range from 0.25 to 0.65 G, and fields of even such small values affect the parameters of photoelectronic multipliers, so magnetic field compensation is necessary.

There are two main methods of magnetic field compensation: passive and active. The passive method of magnetic field compensation is based on the use of special screens made of materials with high magnetic permeability, such as permalloy. The principle of operation of such screens is as follows: during the transition to an environment with a magnetic permeability much higher than the permeability of the external environment, the magnetic induction lines of the external field thicken, thus, the magnetic field inside the permalloy shielded area of space becomes weakened. The passive method requires a complex screen design that ensures the most uniform and continuous distribution of material around each PMT.

The active method consists in using special Helmholtz coils, which create an additional compensating magnetic field, this compensating field is directed opposite to the external magnetic field and as a result the total magnetic field is zero. The advantage of the active method is the possibility of effective compensation of the magnetic field of high values and in a large volume. In addition, this method allows for better control of the compensation field depending on changes in external conditions.

A method is described in Ref. [2] in which the reduction of the influence of a magnetic field on the parameters of a photomultiplier is achieved by rotating the magnetic field lines so that the direction of the magnetic field lines falls on the least sensitive axis of the photomultiplier.

2. Helmholtz coil parameters

The main characteristics of the Earth's magnetic field are the total intensity vector and its components along the coordinate axes. The magnitude of the external magnetic field, in addition to the Earth's magnetic field, depends on the geological conditions of the territory and the objects directly located at the field measurement site.

The magnetic field generated by the current can be calculated as the vector sum of the fields generated by each elementary section of the current [3]. According to Biot−Savart−Laplace law, a current element of length $d\mathbf{l}$ creates a magnetic field with induction

$$d\mathbf{B} = \frac{\mu_0}{4\pi}\frac{I[d\mathbf{l}, r]}{r^3},$$

where μ_0 is the magnetic constant; I is the current strength; $d\mathbf{l}$ is the current element for which induction is calculated; r is the radius-vector to the observation point.

Helmholtz rings comprise a system of identical coils arranged coaxially at a distance equal to their radius. A zone of uniform magnetic field is observed in the center between the coils, the magnitude of which is calculated by the formula

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}}\frac{\mu_0 nI}{R},$$

where n is the number of turns in the coils; I is the current strength; R is the radius of the coils and the distance between them.

The following formula is used to calculate the magnetic field generated by square coils

$$B = 1.01796\frac{2\mu_0 nI}{\pi A},$$

where A is half the length of the side of the coil.

3. Magnetic field measurement

To measure magnetic field induction, a module based on an Arduino microprocessor and a three-axis magnetometer HMC5883L was created. This magnetometer is based on three magnetoresistive sensors. The developed module is capable of measuring magnetic induction up to $B = 8\,\mathrm{G}$, the sensitivity of the magnetometer is $5\,\mathrm{mG}$, which is excessive for measurements of magnetic induction.

In practice, the measured values of the magnetic field include the magnetic fields of neighboring sources. The main sources of interference are hard-iron and soft-iron distortions, which get their name from magnetically hard and magnetically soft ferromagnets. Magnetic hard sources are magnets or other sources of a permanent magnetic field that rotate with the magnetometer and make a constant contribution to its readings. Magnetically soft ferromagnets are magnetized in the Earth's magnetic field and become sources of a magnetic field that varies depending on the position of the ferromagnet in space. They contribute to changing the direction of the magnetic induction vector. Thus, in order to obtain correct magnetometer data, it must be calibrated. The equation for calculating the calibrated values of magnetic induction is as follows:

$$\mathbf{B}_{calib} = S \cdot (\mathbf{B}_{meas} - \mathbf{H}),$$

where $\mathbf{B}_{calib}$ are magnetic field values after calibration; S are coefficients responsible for soft-iron distortion; $\mathbf{B}_{meas}$ are magnetic field values before calibration; $\mathbf{H}$ are coefficients responsible for hard-iron distortion.

To perform calibration, it is necessary to obtain a set of uncalibrated values at different positions of the magnetometer. Then it is necessary to calculate the calibration coefficients for each axis. The distortions from magnetically hard ferromagnets introduce some constant bias to the measured values. Corrections for these distortions are calculated using the formula

$$\mathbf{H}_A = \frac{A_{\min} - A_{\max}}{2} - A_{\min},$$

where $A_{\min}$ and $A_{\max}$ are the minimum and maximum values of the magnetic field for each axis.

The coefficients for eliminating the influence of soft-iron distortion are calculated using the formula

$$\mathbf{S}_A = \frac{B_{\max} - B_{\min}}{A_{\max} - A_{\min}},$$

where $B_{\max}$ and $B_{\min}$ are the maximum and minimum values of the magnetic field for the axis where the difference between these values is greatest; $A_{\max}$ and $A_{\min}$ are the maximum and minimum values of the magnetic field for the axis A.

4. Study of the influence of the magnetic field on the parameters of photomultipliers

Studies of the influence of the magnetic field on the parameters of photomultipliers have been carried out in many papers. For example, measurements were performed in Ref. [4], in which the parameters of photomultipliers were studied depending on their position in the Earth's magnetic field. The magnetic field generated by Helmholtz coils is modeled in Ref. [5], as well as the effect of the residual magnetic field on the parameters of the photomultipliers, depending on their location in the volume of the simulated detector.

The study of the influence of the magnetic field was carried out for Hamamatsu R7081-100 WA-S70 PMT,

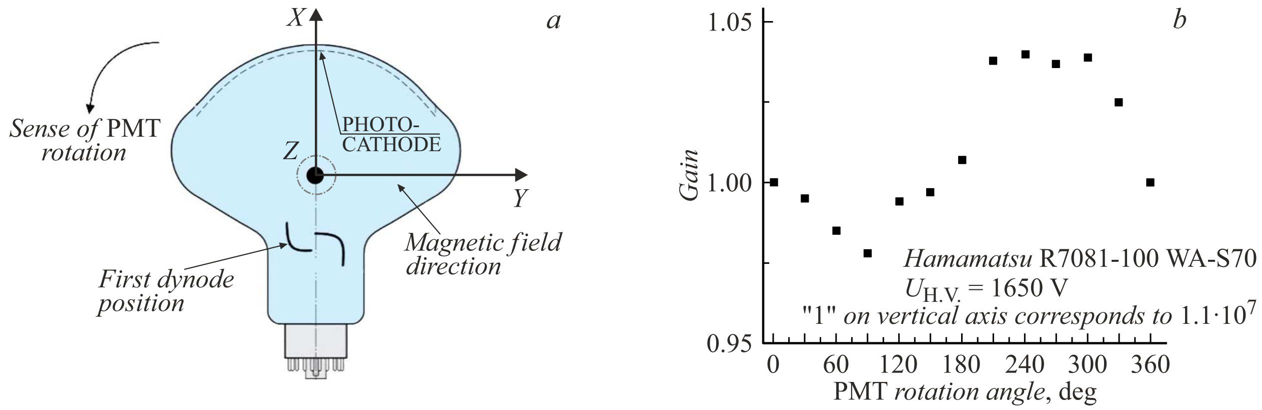

Figure 1. The effect of the Earth's magnetic field on the PMT gain: *a* is the PMT position, top view, *b* is the gain dependence on the angle of rotation of the PMT in the natural magnetic field of the Earth.

which are used in the prototype with a target mass of 5 t [6]. The measurements were carried out in two stages: the first stage included the study of the dependence of the PMT gain coefficient on the Earth's natural magnetic field. The photomultiplier is positioned horizontally on the rotary platform, the illumination of the photocathode is set at such a level that most events occur on single photomultiplier pulses. This level of illumination is achieved at the value of the average Poisson $\lambda_1 = 0.1$, then about 95 % of all events will occur in single photovoltaic pulses. The distance between the fiber optic cable and the photocathode is 70 cm. The platform rotated around its axis counterclockwise with a step of 30°. The photomultiplier is positioned so that the surface of the first dynode is oriented parallel to the vertical component of the magnetic field B_Z. Fig. 1, *a* shows the initial position of the PMT relative to the Earth's magnetic field, as well as the direction of rotation of the PMT during measurements. The magnitude of the magnetic field at the starting point was: $B_x = 0.08$ G, $B_y = -0.22$ G, $B_z = 0.43$ G. Based on the measurement results, the gain coefficients of the photomultiplier were obtained for each rotation angle (Fig. 1, *b*). The spread of the PMT gain during the measurement process was approximately 7 %.

The dependence of the gain coefficient and the time of flight of photoelectrons on changes in the magnetic field were studied at the second stage. For this purpose, a measuring stand was created in which a magnetic field is created by square-shaped Helmholtz coils (Fig. 2). Based on the size of the area in which the magnetic field needs to be compensated, the sizes and parameters of the coils were selected to create a uniform field, and maps of the magnetic induction generated by the coils were constructed. As can be seen from Fig. 2, a uniform field is created in the area between the coils at a distance between them $L = 0.54A$, where A is the length of the coil side. Based on the calculations, three pairs of Helmholtz coils were created to compensate for all three components of the magnetic field. The number of turns in the coils is $N = 5$ to create a field along the horizontal components of the magnetic induction, the number of turns in the coils for the vertical component is $N = 6$. The region of a homogeneous magnetic field is a cube with dimensions $54 \times 54 \times 54$ cm. Each pair of coils is connected to an individual current source, which ensures the independent use of each pair of coils.

During the measurement process, the PMT is in one position perpendicular to the three components of magnetic induction, each of which alternately changes from -0.5 to 0.5 G in 0.1 G increments, and the other two are compensated at this moment. Based on the results of the measurements, the dependences of the PMT gain coefficient and the Peak/Valley ratio (P/V) on the change in the magnetic induction values of each individual component were constructed (Fig. 3). The P/V value is the ratio of the number of events at the peak of the charge spectrum of single photovoltaic pulses to the number of events at the minimum between the pedestal and the peak. For the horizontal component B_Y , the gain change reaches a value of about 20 %, the P/V ratio decreases approximately twofold at the value of the field $B_X = 0.5$ G. BX axis directed along the flight path of the photoelectrons is the least sensitive axis of the PMT, the gain change reaches approximately 5 %, and the P/V ratio decreases by about 1.3 times. The most sensitive axis is directed along the surface of the first dynode, which corresponds to the vertical component of the magnetic field during the measurement process. The PMT gain varies by approximately 22 %, and the P/V ratio decreases by almost 4 times.

The influence of the magnetic field on the time of flight of photoelectrons was also studied using the method described above: one of the components varied from -0.5 to 0.5 G, while the other two components were completely compensated. The illumination of the photocathode is set at such a level that most events occur on single photovoltaic pulses of the PMT. The longitudinal axis of the PMT B_X is the least sensitive, the half-height width of the photovoltaic flight time distribution varies from 2.2 to 2.5 ns, while when the horizontal component B_Y changes, the half-height width (the difference between the

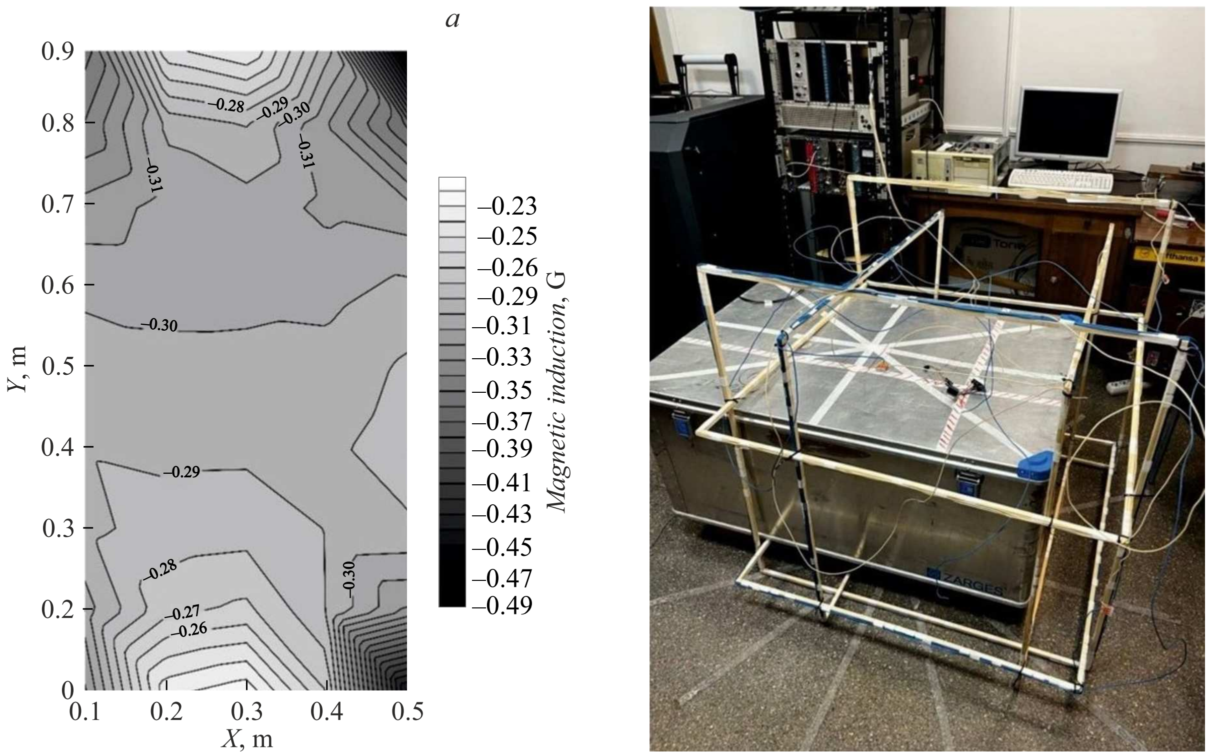

Figure 2. Map of magnetic induction generated by Helmholtz coils (*a*); stand for studying the effect of the magnetic field on the parameters of the PMT (*b*).

maximum and minimum time values taken on the level equal to half the number of events in the peak) lies in the range of 2–5 ns. When the last component B_Z is changed, the half-height width changes from 2 to 2.8 ns (Fig. 4).

Thus, the magnetic field, even of such small values as 0.1 G, affects the parameters of the PMT, so it is necessary to use means to compensate for the magnetic field. To verify the correct operation of the magnetic field compensation system, comparisons were made of the effects of the natural magnetic field and its individual components X and Y. To account for the influence of the vertical component of the magnetic field, the PMT gain was normalized to the value of the vertical component $B_Z = 0.4$ G and amounted to $1.07 \cdot 10^7$. When the photomultiplier was rotated, the horizontal component of the natural magnetic field changed from -0.234 to 0.234 G relative to the transverse axes of the PMT, which led to a change in the gain by 7 %. The change of the BX component in the range from -0.2 to 0.2 G led to a change in the gain from $1.01 \cdot 10^7$ to $1.07 \cdot 10^7$, which corresponds to a relative change of 5 %. For the BY component in the same range, the gain change was from $1.056 \cdot 10^7$ to $1.07 \cdot 10^7$, which corresponds to a change of 1.3 %. Thus, the observed change in the gain coefficient when varying the natural and artificially created magnetic fields turns out to be comparable, which confirms the correctness of the compensation system.

5. Calculation of parameters of Helmholtz rings and the field created by them for BLNT

According to the international analytical model of the geomagnetic field (IGRF-13) [7], the values of the components of the total vector of the Earth's magnetic field in the area of the BLNT prototype are: $B_X = 0.23$ G, $B_Y = 0.03$ G, $B_Z = 0.44$ G. In order to reduce the background of gamma radiation emanating from the surrounding rocks, the walls of the main hall of the laboratory of the Gallium-Germanium Neutrino Telescope (GGNT) are lined with steel sheets that distort the magnetic field. Taking into account these distortions, as well as the properties of the surrounding rocks, additional measurements of the magnetic field were carried out to accurately determine its parameters at the detector installation site. The measured values obtained differed from the calculated ones: $B_X = 0.15$ G, $B_Y = -0.22$ G, $B_Z = 0.25$ G, with the horizontal component being $H = 0.26$ G [8].

A cylinder with a height of 32 m and a radius of 15.5 m was used to calculate the parameters and configuration of the Earth's magnetic field compensation system for the BLNT. The vertical component will be compensated by using 3 rings with ten turns each, which are located in horizontal planes around the detector with a distance between the rings of 16 m. Compensation of the horizontal component is achieved using 12 rings with seven turns in

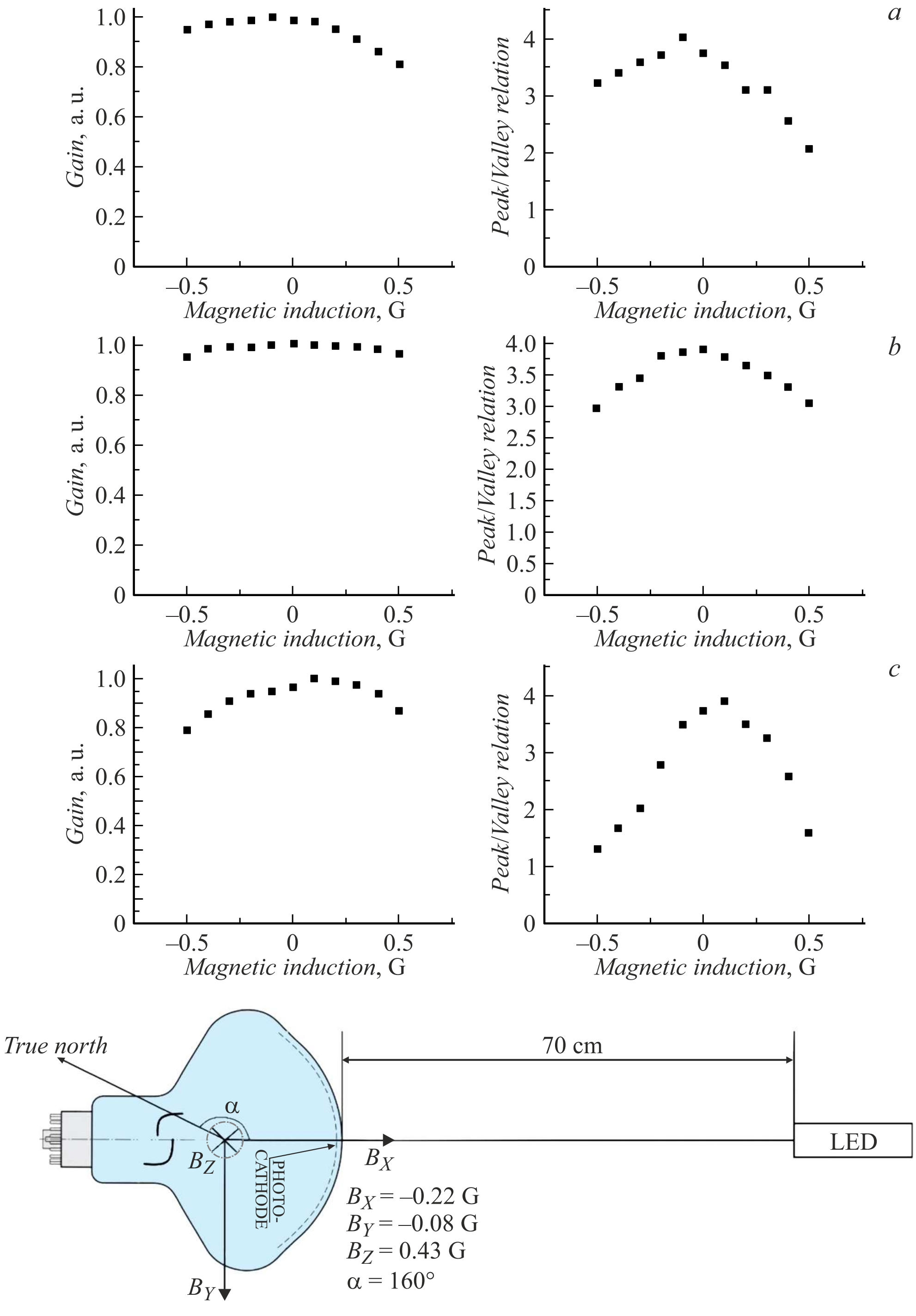

Figure 3. Dependence of the gain coefficient and the P/V ratio for single-photovoltaic illumination of a photocathode on changes in magnetic field induction: *a* — along the component *X*; *b* — along the component *Y*; *c* — along the component *Z*.

each. These coils are arranged in vertical planes around the vertical axis of the detector. The angle between the coils is 30°.

Before calculating the magnetic induction, a set of points in space is created in which the magnetic field must be compensated. When calculating the generated field, the coils are divided into small elements, for each of which the magnetic induction is calculated at a selected point in space, then the vector sum of the magnetic induction from all elements of the coils is calculated at this point. As a result of the calculations, magnetic induction maps were constructed for vertical and horizontal components (Fig. 5–7). Coils designed to compensate for the horizontal component create a uniform field throughout the volume. When using 12 rings with seven turns, each creates a uniform magnetic field of the horizontal component H of

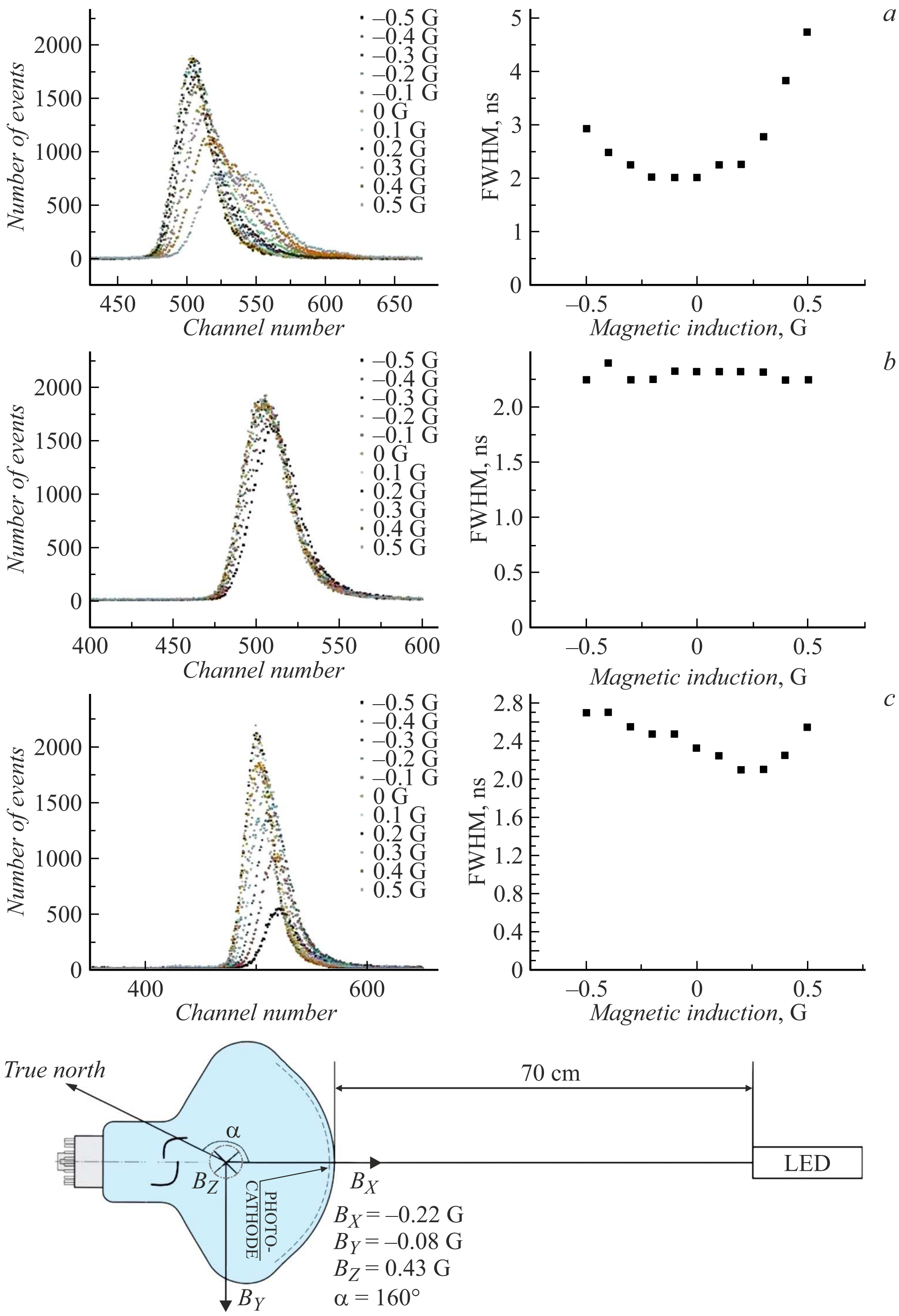

Figure 4. Dependence of the time-of-flight distributions of photoelectrons during single-photovoltaic illumination of a photocathode on changes in magnetic field induction: *a* — along the component *X*; *b* — along the component *Y*; *c* — along the component *Z*.

0.25 G at a current of 24 A. Coils designed to compensate for the vertical component B_Z also create a uniform magnetic field along the vertical axis with a magnitude of 0.25 G. In this case, 3 rings of 10 turns are used at a current of 40 A.

The general view of the detector is shown in Fig. 8.

6. Calculation of heating of conductors of the magnetic field compensation system

One of the limiting criteria for using an active compensation method is the heat generation of Helmholtz

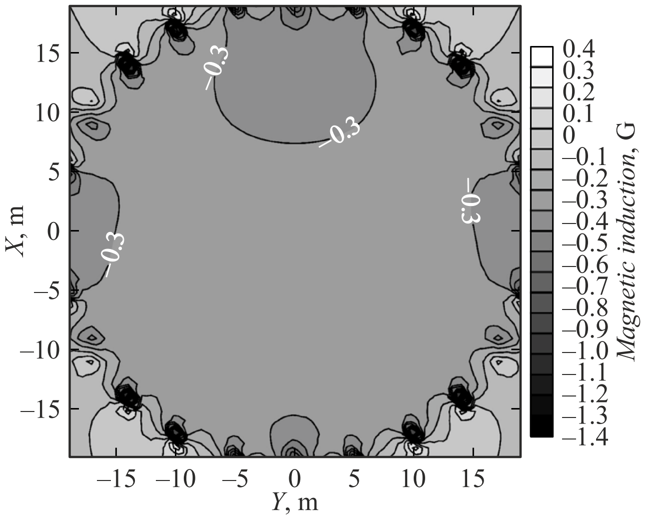

Figure 5. Map of magnetic induction generated by coils in the direction of the X axis.

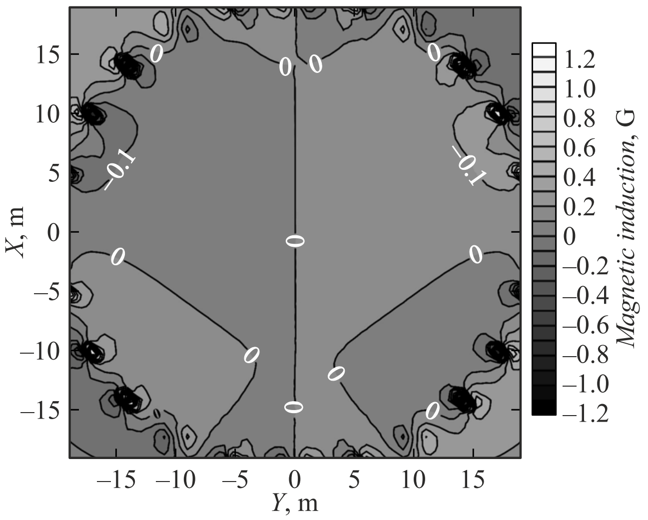

Figure 6. Map of magnetic induction generated by coils in the direction of the axis Y.

coils, which will be spent on heating the environment. Therefore, it is necessary to determine the total heat flow at which the equilibrium of the conductor−medium system occurs, and no further heating of the environment occurs. After determining the equilibrium heat flow, the maximum allowable current for the magnetic field compensation system can be determined.

According to Joule−Lenz law, the amount of heat released in a conductor is proportional to the resistance, the square of the current strength, and the time interval:

$$Q = I^2 Rt.$$

Depending on the intensity of fluid movement, two main modes of movement are distinguished: laminar and turbulent.

The algorithm for calculating the heating of a conductor consists in determining the type of convective heat transfer and the object for which the heat exchange is calculated, introducing defining parameters, determining the flow mode of the fluid, calculating the heat transfer coefficient and finding the convective heat transfer coefficient [9].

In this case, free convection is used to calculate the heat exchange between the rings and the medium. Then the dimensionless heat transfer coefficient (Nusselt criterion, N_u) depends on the product of the Grasgoff criteria (Gr) and Prandtl criteria (Pr) (Rayleigh criterion (Ra)). The criterion Gr is calculated using the formula

$$Gr = \frac{gR_0^3}{\nu^2}\beta\Delta T,$$

$$Pr = \frac{\nu}{a},$$

where R_0^3 is the defining dimension, [m]; β is the volumetric expansion coefficient, [1/K]; a is the kinematic viscosity coefficient, [m^2/s]; ΔT is the temperature difference; a is the thermal conductivity coefficient.

For vertical rings, the calculation was carried out for the vertical and horizontal parts separately. For the vertical part, the value of the criterion Ra is $Ra = 396.7 \cdot 10^{10}$,

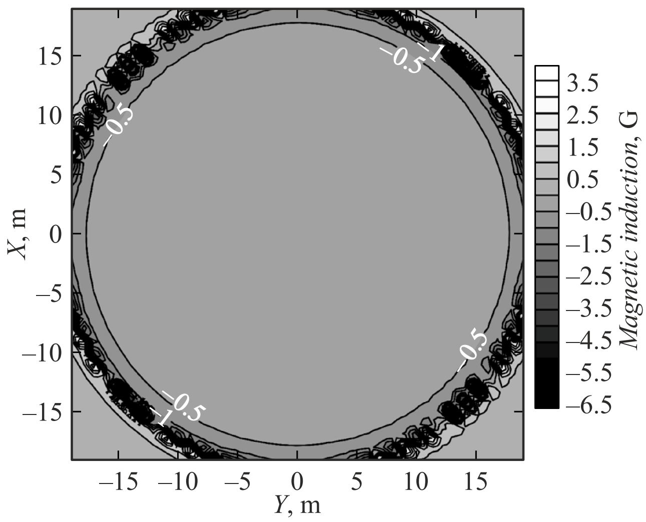

Figure 7. Map of magnetic induction generated by coils in the direction of the axis Z.

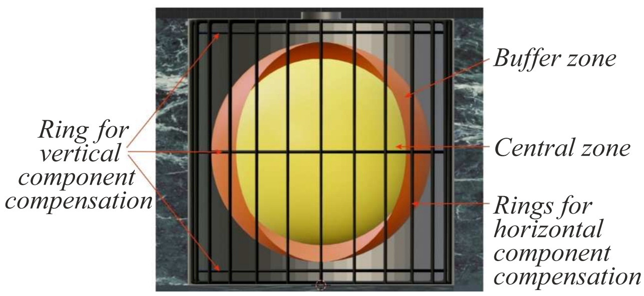

Figure 8. General view of the detector.

for the horizontal $Ra = 3967$ when the ambient volume is overheated by 1 °C. Thus, the formula for calculating the criterion Nu for the vertical section will have the form

$$Nu = 0.15Ra^{0.333}\varepsilon_t,$$

for horizontal section—

$$Nu = 0.5Ra^{0.25}\varepsilon_t,$$

where ε_t is the temperature correction, which was assumed to be equal to one for simplicity of calculations. The value of the criterion Nu for the vertical section is 2351.68 and 3.97 for the horizontal section. The next step is to calculate the heat transfer coefficient using the formula

$$\alpha = \frac{Nu\lambda}{R_0},$$

where λ is the coefficient of thermal conductivity, [W/(m·°C)]. The amount of heat flow lost to the environment is determined by the formula:

$$Q = \alpha\Delta TF,$$

where F is the surface area of the conductor, [m^2]. The heat flow lost by the vertical section is 122.2 W, the heat flow lost by horizontal section is 225.9 W. The total heat flow for vertical rings is 58480.8 W. The heat flow lost by the horizontal rings is 21291 W. Then the maximum allowable current flowing in the conductor can be calculated using the formula

$$I = \sqrt{\frac{Q}{R}},$$

where R is the resistance of the conductor. The maximum allowable current according to the calculation results is 127.9 A, which is three times the current at which the magnetic field compensation system for the BLNT will be used. Thus, when using Helmholtz coils to compensate for the Earth's magnetic field, the heating of the surrounding volume will not exceed 1 ° C.

Conclusion

A system for compensating the Earth's magnetic field for the BLNT has been developed. In the course of the study, an active method of magnetic field compensation was considered, an algorithm was developed for calculating the compensation magnetic field, selecting the parameters of Helmholtz coils, and calculating the heating of these coils. The use of an active magnetic field compensation method makes it possible to create a uniform magnetic field in a large volume of space for both horizontal and vertical components separately. The calculations were based on a cylinder with a height of 32 m and a radius of 15.5 m. As the calculation results show, the residual magnetic field in the required volume is at the level of 0.05 G, which does not affect the PMT. In addition, this approach makes it possible to study the effect of a magnetic field of various amplitudes on the PMT. As part of the study, a magnetometer was assembled, the magnetic field was measured at the detector location, and a stand was developed to study the effect of the magnetic field on the parameters of photomultipliers. The dependences of the PMT gain coefficient and the P/V ratio on changes in magnetic induction are also investigated.

Thus, the use of Helmholtz rings is an effective method for forming a uniform magnetic field that can be used to compensate for the Earth's field. Unlike using materials with high magnetic permeability, this method is more affordable and easier to implement.

Funding

Supported by the Ministry of Education and Science of the Russian Federation within the framework of the program for financing major scientific projects of the national project „Science", № 075-15-2024-541.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] N.A. Ushakov, A.N. Fazliakhmetov, A.M. Gangapshev, V.N. Gavrin, T.V. Ibragimova, M.M. Kochkarov, V.V. Kazalov, D.Yu. Kudrin, V.V. Kuzminov, B.K. Lubsandorzhiev, A.D. Lukanov, Yu.M. Malyshkin, G.Ya. Novikova, V.B. Petkov, A.A. Shikhin, A.Yu. Sidorenkov, E.P. Veretenkin, D.M. Voronin, E.A. Yanovich. J. Phys. Conf. Ser., 1787, 012037 (2021). DOI: 10.1088/1742-6596/1787/1/012037

[2] A. Ianni, G. Korga, G. Ranucci, O. Smirnov, A. Sotnikov. *Compensating the influence of the Earth's Magnetic Field on the scintillator detector resolutions by PMTs orientation.* LNGS preprint INFN/TC-00/05, 2000. DOI: 10.15161/oar.it/1448986128.29

[3] I.V. Saveliev. *Kurs obshchei fiziki, tom 2. Elektrichestvo i magnetizm. Volny. Optika*: uchebn. posobie (Nauka. Glav. red. Fizmatlit, M., 1982), 2-e izd., pererab.

[4] E. Leonora, S. Aiello, G. Leotta. IEEE Transactions on Nucl. Sci., **59** (4), 1259 (2012). DOI: 10.1109/ANIMMA.2011.6172838

[5] S.R. Cabo, Ya. Nishimura, S.L. Suárez Gómez, L. Bonavera, M.L. Sánchez, J.D. Santos, F.J. de Cos. *Optimization of geomagnetic shielding based on detection efficiency*. arXiv preprint arXiv:2503.14380. (2025), DOI: 10.48550/arXiv.2503.14380

[6] N. Ushakov, A. Fazliakhmetov, V. Gavrin, T. Ibragimova, B. Lubsandorzhiev, A. Lukanov, A. Shikhin, A. Sidorenkov, D. Voronin. *Evaluation of large area photomultipliers for use in a new Baksan Large Neutrino Telescope project.* PoS(ICRC2021)1101. DOI: 10.22323/1.395.1101

[7] Electronic resource. Available at: http://serv.izmiran.ru/webff/igrf-13gm.html
[8] A.D. Lukanov, D.M. Voronin, A.N. Fazliakhmetov, E.P. Veretyonkin, A.M. Gangapshev, V.N. Gavrin, T.V. Ibragimova, V.V. Kazalov, V.V. Kuzminov, B.K. Lubsandorzhiev, Yu.M. Malyshkin, D.A. Nanzanov, G.Ya. Novikova, V.B. Petkov, A.Yu. Sidorenkov, O.Yu. Smirnov, N.A. Ushakov, A.A. Shikhin, E.A. Yanovich. Bull. Russ. Acad. Sci. Phys., **87**, 929 (2023).
[9] V.P. Isachenko, V.A. Osipova, A.S. Sukomel. *Teploperedacha* (Energiya, M., 1975)

Translated by A.Akhtyamov