SYSTEM FOR MEASUREMENT OF MAGNETIC FIELD LINE STRAIGHTNESS IN SOLENOID OF ELECTRON COOLER FOR COSY

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Abstract

Construction of measurement system is presented. The system is based on special magnetic sensor (compass) with a mirror attached to the compass needle. The needle with the mirror are suspended on gimbal suspension and can rotate in two directions. Measuring reflected laser beam deflection one can measure field line straightness with accuracy up to 10^{-6} rad. The compass is installed inside vacuum volume of the cooling section on special carriage that moves on rail along the section via special tape. To calibrate the compass special test bench was made. The calibration procedure allows to determine and to diminish compass inaccuracy appeared during manufacture and assembling. Results of calibration of the compass on the test bench are presented.

INTRODUCTION

Straightness of magnetic field line in cooling section is very important for electron cooling as it increases effective velocity of electrons. For high energy electron cooling it is especially important as the influence increases with energy $V_T=\gamma V\theta$, where γ – relativistic factor, V – longitudinal velocity of an electron, θ – angle of field line deflection.

Experience with production of electron coolers shows that straightness of magnetic field line degrades with time. Because of this a new device which allows to measure straightness with period of several months without disassembling of vacuum chamber is needed. For 2 MeV cooler for COSY it was proposed to install measuring system based on magnetic compass inside the vacuum chamber of cooling section and toroids. Similar system was used on electron cooler for NAP-M storage ring [1].

The transverse components of the magnetic field of coil can be determined by the magnitude of deviation from the axis of magnetosensitive element of sensor. If it is rigidly connected with the mirror, the angle of deviation can be determined from the shift of the light spot produced by a beam from an external source, reflected by the mirror. Returning a spot in the starting position by the influence of compensating magnetic field from an external source, the magnitude of corresponding component of field of tested solenoid (i.e. misalignment of field line at that point) can be determined.

In the first experiments on determination of the quality of magnetic field in INP [1], an optical automatic autocollimator was used as the measuring system, in which the angle of deflection was determined by the mechanical adjustment of the light in the instrument. As the magnetic sensor it was used a construction composed of the mirror, laid down in the gimbal suspension with jewels from clock as the bearing supports, and of steel rod penetrating the mirror axis. In a magnetic field of a solenoid with magnitude of about 1 kG field inhomogeneity about 10^{-5} radian was determined. The sensitivity was limited mainly by friction at the nodes of motion in the optical components of the collimator during the rearrangement of its optics.

In 2000, in the BINP a measurement system for a prototype of electron cooling system for the Tevatron (Fermilab, USA) was designed [2]. For operating magnetic field of 50-100 G sensitivity of previous devices was not enough, therefore the measuring system was modernized.

The mirror was fixed on the end of a light frame along which axis a magnet (cylinder of material NdFeB) was inserted. At another end a nonmagnetic counterbalance was attached. With the help of wire, fixed at the center of gravity, the sensor node was suspended in the center of a hollow cylindrical carriage, which had compensating circuits. The carriage was moved along the bottom of a narrow chamber and was stabilized by two strings, stretched along the pipe.

Electronic circuit contained a low power semiconductor red laser as light source, four quadrant photodiode, source of compensating current and the feedback loop, allowing return reflected from the mirror compass beam to the starting position for fixing the value of the compensation current.

This scheme with no significant changes was used in future for setting up solenoids of produced at the BINP coolers for IMP (Landzhou, China) and for CERN. Only constructions of compasses were improved.

Such constructions of compasses are highly sensitive due to the absence of nodes with the mechanical friction. But they can not be used in the COSY because of limited strength of thin metal suspension wires. This can result in break of the wire especially on curved parts of magnetic system. Such situations are inevitable since the compass need to be removed from a region with homogeneous field to release accelerator's aperture. Increasing the strength of wire by increasing its thickness is also limited because of rapid growth of the elastic forces. Significantly more durable fishing line is not a vacuum material and it does not allow heating to even 100 degrees.

For these reasons for 2 MeV COSY cooler a design (already described above) with setting the magnet to the mirror in a gimbal suspension was chosen (fig. 1).

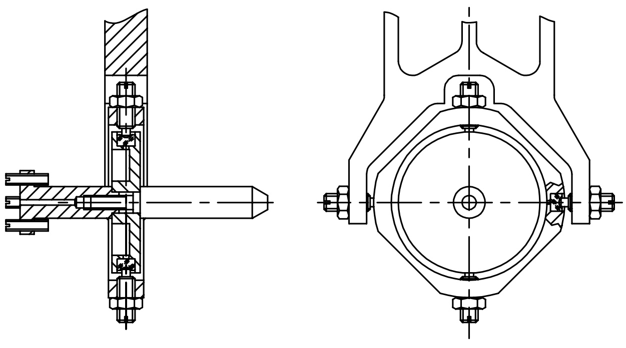

Figure 1: Compass with gimbal suspension.

Since it can rotate in every direction the compass always sets along the field, minimizing the transverse loads from the strong magnetic field.

In the COSY cooler the carriage with a compass is moved along the axis of the solenoid on a massive rail which ensures the stabilization of the carriage in transverse direction (fig. 2).

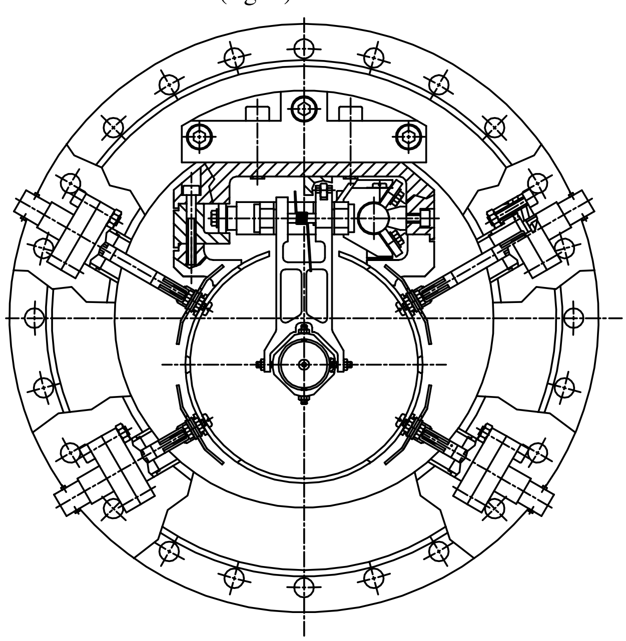

Figure 2: Rail with compass inside the vacuum chamber.

Rail is located at the top of the vacuum chamber, the frame of a compass mounted on a carriage underneath. The carriage is moved along the rail by a closed perforated tape, which moves with a help of a special gear. Near one end of the cooling solenoid the holder goes from vertical to horizontal position, raising the compass, so that the aperture of the accelerator is released.

TEST BENCH

An important part of the whole complex for the production and regulation of electron cooling is test bench for the magnetic measurements. Such a device as a compass can not be manufactured in a production environment with perfect accuracy. Because of this the compass is not balanced, and the mirror is not perpendicular to the magnetic axis. Therefore, before installing it in the cooler the compass should be tested and the deviation from the norm of the parameters should be minimized.

The procedure for adjusting the compass is measuring its parameters and possible elimination of distortions. It should be noted that the residual small defections of parameters don't influent on the quality of measurement of filed line straightness in the cooler, and lead only to consumption of additional compensating currents, resulting in pedestal in results of measurement (systematic error).

On fig. 3 a scheme of the test bench is shown. Compass (1) is installed in center of main solenoid (2), which is powered with a supply (3). The solenoid also contains block of correction and calibration coils (4). Laser beam from source (5) is directed on cube (6) which partly reflects the beam on mirror of the compass. The mirror reflects the beam in opposite direction to prism and then to photodiode (7). By the signals on four sectors of the photodiode, electronic block of feedback system (8) produces signal for correction power supplies (9) in order to place the beam in center of the photodiode. Components of the transverse magnetic field in the compass region are proportional to the currents in correction coils. Another laser (10) is used only for adjustment of the test bench.

The solenoid can be rotated to 180 degrees without correction and calibration coils. It is important for measurements which will be described below.

EXPERIMENTS

Measuring parameters of sensor

For measurement of compass parameters we used the same method that was used for previous compasses on another test bench [3]. Briefly, the idea of the method is as follows. The signal recorded by the instrument in some point includes several components. Some of them depend on the solenoid's longitudinal magnetic field B_z, and the others are field-insensitive. This signal can be represented by the following expression:

$$B_j = B_{1j} + B_{0j} + \delta B_j = B_j[\alpha_j + \beta_j + \gamma_j] + \\ + [B_j^{ext} + B_j^{sh} + B_j^{sen}] + \delta B_j$$

where j is the x or y coordinate; α_j are the imperfections of the solenoid's magnetic field; β_j is the angle between the magnetic axis of the compass and the perpendicular to the mirror; γ_j is the angle between the solenoid's axis and the laser beam, B_j^{ext} is the external (with respect to the solenoid) magnetic field; B_j^{sh} is the residual field of the magnetic shield; B_j^{sen} are the additional z-independent components due to the magnet's unbalance etc.; and δB_j are the random noises.

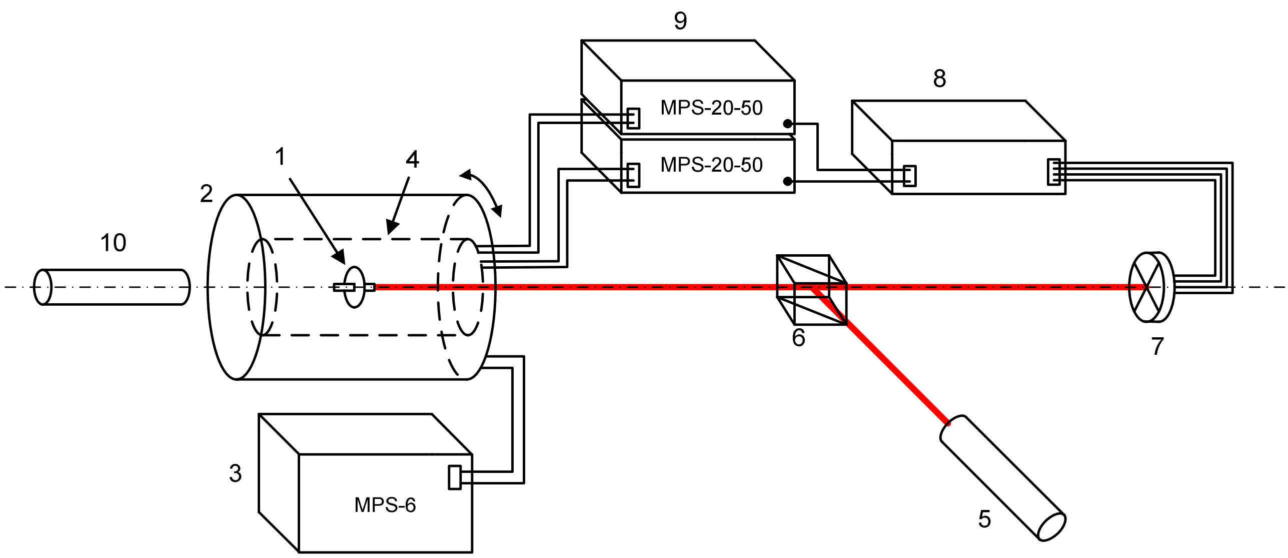

Figure 3: Scheme of the test bench.

The components B_{1j} and B_{0j} can basically be found separately by making measurements with different solenoid currents (fields). Parameters β_j, γ_j, and B_j^{sen} (as well as δB_j) are the measurement errors, but they can be reduced to small values by aligning both the compass and the optical channel of the whole measuring system.

If we exclude random factors and take into account that the laser beam can be aligned with the solenoid's axis with deviation $\gamma_j \sim 1 \cdot 10^{-4}$ rad, the main sources of errors appear to be related to the magnetic sensor's properties. Parameters B_j^{ext} and B_j^{sh} can be ignored due to high properties of the magnetic shield. Under these conditions, equation for B_j becomes simpler and contains only three components:

$$B_j = B_z[\alpha_j + \beta_j] + B_j^{sen}.$$

Rotation of the solenoid about its axis through 180 degrees reverses the signs of its own transverse components. Making three measurements for each of components x and y in order to determine $B_{j1}(B_{z1})$, $B_{j2}(B_{z2})$, and $B_{j3}(B_{z3})$ for the fields B_{z1}, $B_{z2} = 2B_{z1}$, and $B_{z3} = -B_{z2}$ (i.e., with the solenoid turned over) allows all of the values characterizing the quality of the compass to be calculated:

$$B_j^{sen} = 2B_{j1} - B_{j2}, \alpha_j = (B_{j2} - B_{j3}) / 2B_{z2}$$

$$\beta_j = (B_{j2} + B_{j3} - 2B_j^{sen}) / B_{z2}.$$

After adjustment of parameters we reached next values: B_x^{sen}/B_y^{sen}=-5.4·10^{-4}/4.4·10^{-4}; α_x/α_y=1.1·10^{-4}/5.7·10^{-4}; β_x/β_x=8.6·10^{-4}/-8.1·10^{-4}. Such values are appropriate to use the compass for measurement of field line straightness.

Friction in nodes

It was said above that disadvantage of the gimbal suspension is friction force in jewel bearings which can reduce sensitivity and accuracy of the sensor. In fig. 4 one can see set of curves which were measured by slow changing of current in correction coils without feedback. There are four pictures with dependence of signal on photodiode on current in the coils, where red lines show results which were measured changing current from -3 A to 3 A, and blue lines – changing current back from 3 A to -3 A. From the figure one can see there is hysteresis related with friction in bearings, but in the same time influence of friction force decreases with increasing of solenoid field.

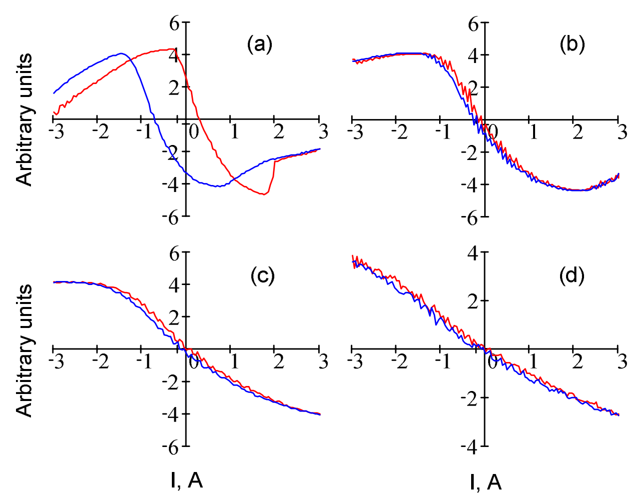

Figure 4: Hysteresis due to friction. a) *B*=38 G, b) *B*=62.5 G, c) *B*=125 G, d) *B*=250 G.

Position of compass is determined by equilibrium between moments of friction force and of magnetic force which acts on magnetic rod of the sensor. In a simple model of the magnetic dipole in longitudinal field the moment of magnetic force is equal to:

$$M_m = q_m B L \alpha$$

where B – magnetic field, L – length of the rod, α – angle between force line and the rod, $q_m = S \cdot B$ – magnetic charge, S – sectional area of the rod. Since friction force doesn't depend on magnetic field, the angle α depends on magnetic field as $1/B^2$.

In fig. 5 a dependence of angle between magnetic field line and sensor's rod, calculated form hysteresis, is sown. The blue line is a fitting curve ~*1/B*^{2}.

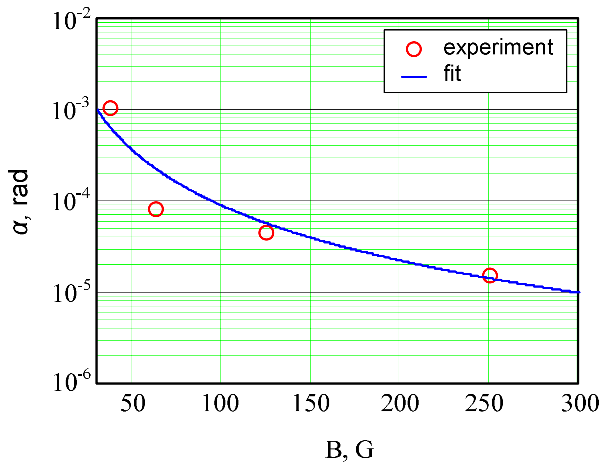

Figure 5: Residual angle due to friction.

Interpolating the results for 2 kG we can get that uncertainty of angle related with friction in bearings is about $2 \cdot 10^{-7}$, that is much lower then needed accuracy of measurements 10^{-5}.

Sensitivity of the compass

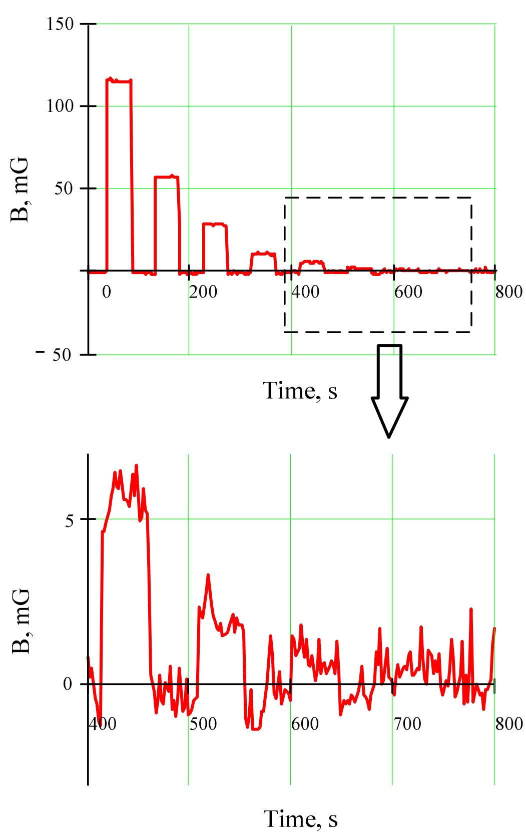

Figure 6: Sensitivity of the compass.

To measure sensitivity the calibration coils were used. On fig. 6 the response of correction coils for the turning on current in calibration coils is shown.

The signal on calibration coils has a step form with decreasing amplitude (from left to right: 2 A, 1 A, 0.5 A, 0.2 A, 0.1 A, 0.05 A, 0.02 A, 0.01 A, 0.005 A, 0.002 A, 0.001 A) and interval with zero signal between two steps. Length of a step and interval between steps are 45 seconds (period 90 sec). 1 A in calibration coil corresponds to field 55 mG in compass region.

From fig. 6 one can see that response from step 0.02 A (region of 600 sec) is the last one that can be distinguished from measurement noise. So sensitivity of the compass is about 1 mG. For field in cooling section 1 – 2 kG such sensitivity means that we can measure angle of field line with accuracy $(0.5 – 1.0) \cdot 10^{-6}$.

CONCLUSION

Measurements of parameters of compass with gimbal suspension, which were made on special test bench, show that it can be used in cooler for COSY to measure magnetic field line straightness with accuracy better then 10^{-5} for field 1 kG and more. At the same time such system has some disadvantages, such as worse sensitivity and accuracy in comparison with compass on wire suspension. However compass with wire is not appropriate to use it in system for measurements without disassembling of vacuum chamber.

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