The progress report on development of the magnetic field measurement technique

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During 2004-05 years the efforts of the Dubna team were concentrated on manufacturing of the Hall and NMR magnetometer and generation proposals for solving the problem of 'zero' field for spectrometer magnet.

1. Hall and NMR magnetometers, equipment for the magnetic field measuring bench

The Hall and NMR magnetometers were successfully designed, manufactured, tested and calibrated. Fig.1 and 2 shows the view of those magnetometers with the tables of parameters as they were presented on the cover page of the JINR News [1]. The next step for the magnetic field measurement bench realization may be the request of 4.5 m linear encoder for accurate positioning of measurement head in longitudinal direction. It may be the HIDENHAIN Linear Encoder LIDA 485 with the accuracy ±5 μm (in case of using a calibration curve - ±1 μm). The price of this equipment 4400 Euro (PC card included). The table of parameters is in Fig.2.

МАГНИТОМЕТРЫ MAGNETOMETERS

Специалистами ОИЯИ разработаны прецизионные ядерный NM-2
и холловский HM-16 магнитометры на линии с ЭВМ.

JINR specialists have developed the precision magnetometers NM-23 (nuclear type) and HM-16 (Hall type) on-line connected to the comput

Nuclear Magnetometer NM-23

Range of field measued	0.05–3 T
Accuracy	Up to 0.001%
Search for resonance	Automatic

Hall Magnetometer HM-16

Range of field measued	From hundredths of tesla to several T
Accuracy	0.01%
Probe (20x12x8 mm)	With thermostat

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Fig.1. NMR and Hall Magnetometers

Exposed Linear Encoders
LIDA

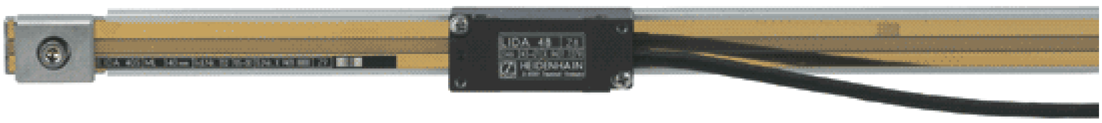
LIDA incremental linear encoders use AURODUR steel scales with grating periods of 20 µm (LIDA 400) or 40 µm (LIDA 100) as measuring standard. The new LIDA models are relatively insensitive to scale contamination and unevenness of the mounting surface.

LIDA 400

- Measuring lengths up to 30 m
- High traversing speed
- For limited installation space
- Signal period 20 µm

	LIDA 475 **LIDA 485**	**LIDA 477** **LIDA 487**
Measuring standard/ Grating period	AURODUR steel scale tape with AURODUR graduation 20 µm	
Output signals	**LIDA 475:** TTL **LIDA 485:** 1 V_{PP}	**LIDA 477:** TTL **LIDA 487:** 1 V_{PP}
Signal periods	**LIDA 475:** 4 µm / 2 µm **LIDA 485:** 20 µm	**LIDA 477:** 4 µm / 2 µm **LIDA 487:** 20 µm
Accuracy grades	± 5 µm	± 15 µm
Recommended measuring steps	To 0.1 µm	To 0.1 µm
Max. traversing speed	Max. 480 m/min at -3dB cutoff frequency >200 kHz	
Measuring lengths ML	140 to 30040 mm	240 to 6040 mm
Reference mark	One at midpoint of measuring length	

LIDA 475, LIDA 485



- For long measuring ranges up to 30 m
- For measuring steps of 1 µm to 0.1 µm
- Integral limit switches

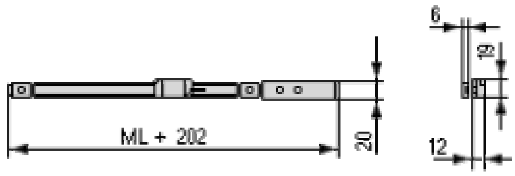


Fig.2. Parameters of the HIDENHAIN Linear Encoder

2. Measurement of 'zero' magnetic field for spectrometer magnet

For the magnetic spectrometer BPMs calibration the main magnet field has to be close to zero. The 'zero' field requirements for two levels 10^{-5} and 10^{-6} are presented in Tab.1 (for magnetic field integral and point field).

Table 1. 'Zero' magnetic field requirements

	Minimal spectrometer energy (45 GeV)	Maximal spectrometer energy (400 GeV)
Nominal integral (T*m) point field (T)	 0.15 0.05	 1.33 0.44
'Zero' as 10^{-5} integral (mT*cm) point field (μT)	 0.15 0.5	 1.33 4.4
'Zero' as 10^{-6} integral (mT*cm) point field (μT)	 0.015 0.05	 0.133 0.44

For the measurement of "zero" magnetic field at the LNP it was proposed to use:

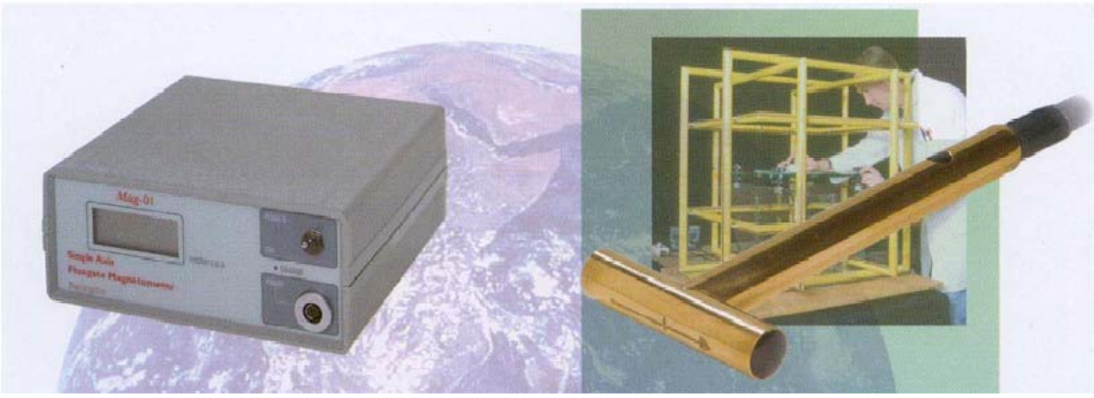
- fluxgate magnetometer
- vibrating wire technique

Some parameters for those techniques are in Tab.2. The fluxgate magnetometer is more suitable for point magnetic field measurements, the vibrating wire one – for integral measurements. Parameters of possible fluxgate magnetometer of Bartington manufacture is in Fig.3.

Table 2. Parameters of techniques for ‘zero’ field measurement

	Fluxgate magnetometer	Vibrating wire
Resolution	0.01-0.001 (μT)	0.01-0.02 (mT*cm)
Price (kEuro) West Russia	 4 – 8 0.6 - 1	

Bartington Instruments



Measurement range / Resolution (LCD display)

Magnetometer	Low field probes		High field probes	
	Range (μT)	Resolution (nT)	Range (μT)	Resolution (nT)
Mag-01	0-20	1	0-200	10
	20-200	10	200-2000	100
Mag-01H (X10 sensitivity)	0-2	0.1	0-20	1
	2-100	1	20-1000	10
	100-290	10	1000-2000	100

Fig.3. Parameters of fluxgate magnetometer

3. Test bench for vibrating wire technique

For the first time the VWT was realized by A.Temnykh. It is described in [2 – 4]. For VWT testing and sensitivity determination a test bench was manufactured and commissioned at the LNP. The test bench setup was realized according to the scheme Fig.4.

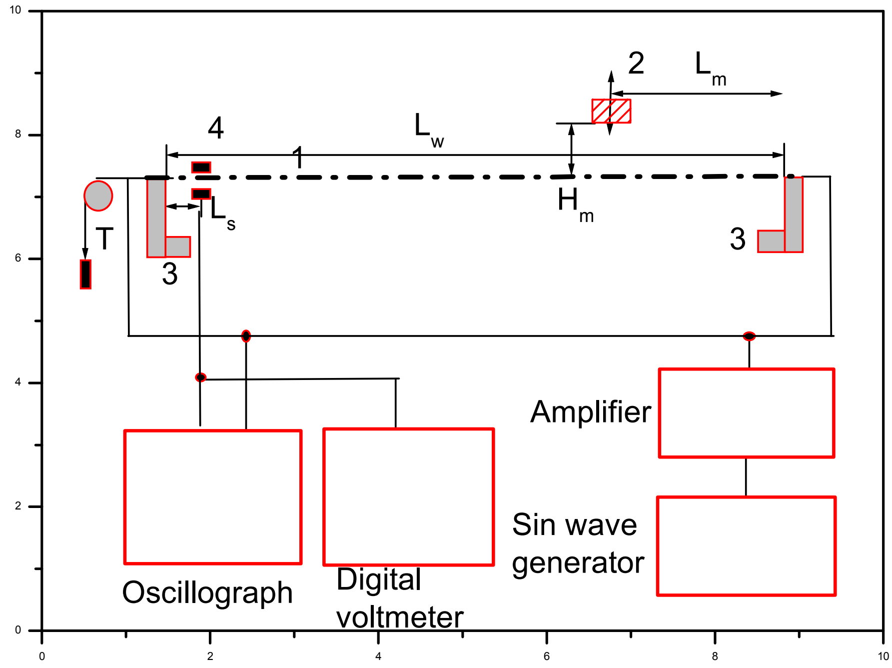


Fig.4. The measurement setup scheme. 1 - streched wire, 2 – test ring PM, 3 – stages, 4 – horizontal wire motion sensor.

A wire 1 (copper-beryllium, L_W=2.55 m, $\varnothing_W$=0.19 mm) was streched between two stages 3 under tension T=2.1 N. This gives the first fundamental frequency of the wire vibration ~18 Hz. A phototransistor-LED assembly (Proton corp., Russia, К3ПРЛ 01Д-0/25.3) was deployed as a wire position monitor 4. At the test bench only the vertical magnetic field component was measured and that is why the horizontal wire motion sensor was in use. The detector was placed L_s=75 mm from the wire end. A small ring PM at the L_m=0.638 m was used for the test magnetic field creation. The strength of the field controlled by the distance H_m between magnet and wire. The wire driving current was generated by Sin wave generator (Г3-123) and amplified by the LNP made amplifier to the maximal value I_w=0.7 A. The signals from the driving current and the wire motion sensor were observed by the analog oscillograph (C8-17) and the sensor signal measured by the digital voltmeter (В7-27). A very important improvement was inserted into the test bench design. A.Temnykh and we have observed a large sensor signal instability. The main reason of it was the occasional air flow in the experimental hall which causes the direct mechanical interference with the wire and changing the condition of the wire cooling. For this effect removing we have surrounded the wire by the plastic tube. After this improvement the signal stability and the tolerance of the measurements was increased in some times. Some views of the test bench are presented in Fig.5-11.

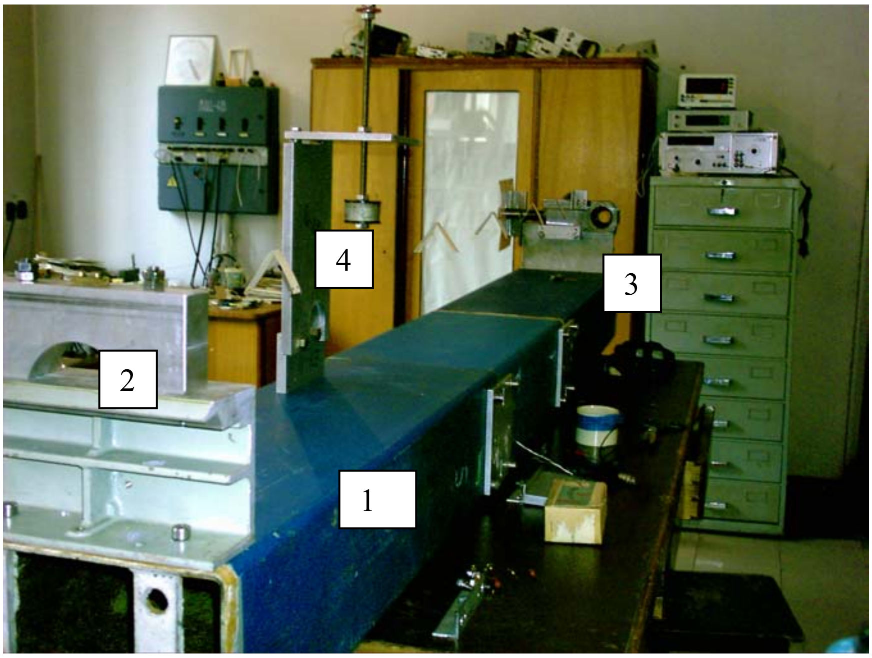


Fig.5. Overall view of the test bench
1 – steel table;
2 – stage with fixed end of wire;
3 – stage with end of wire under tension (Fig.3-5);
4 – tested PM (Fig.6).

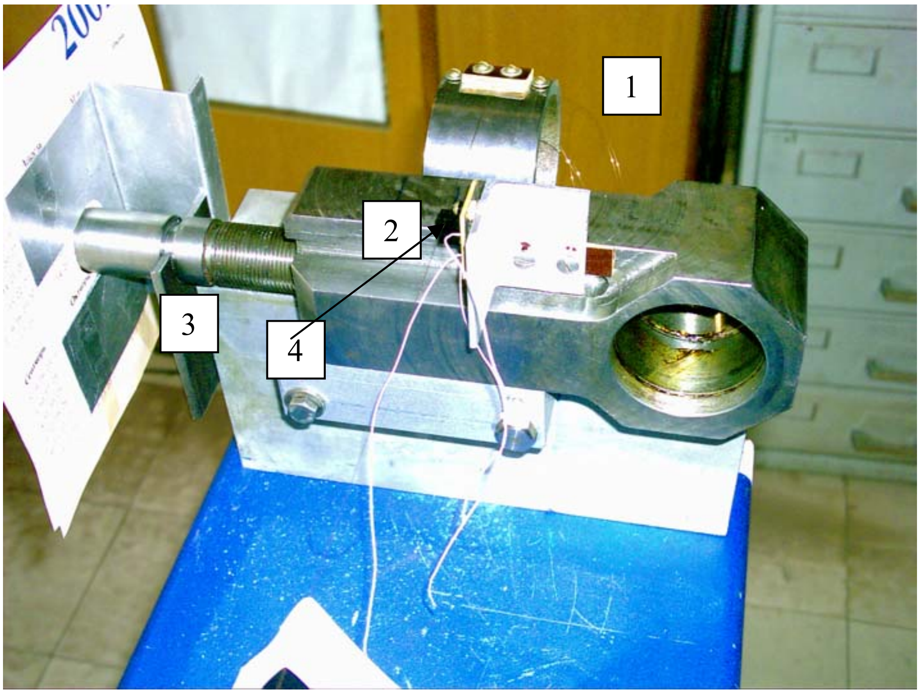


Fig.6. View of the stage with tensioned end of wire.
1 – cylinder for the wire end fixation and tensioning;
2 – moving support for the optic sensor position adjustment;
3 – screw for the support moving;
4 – optic sensor.

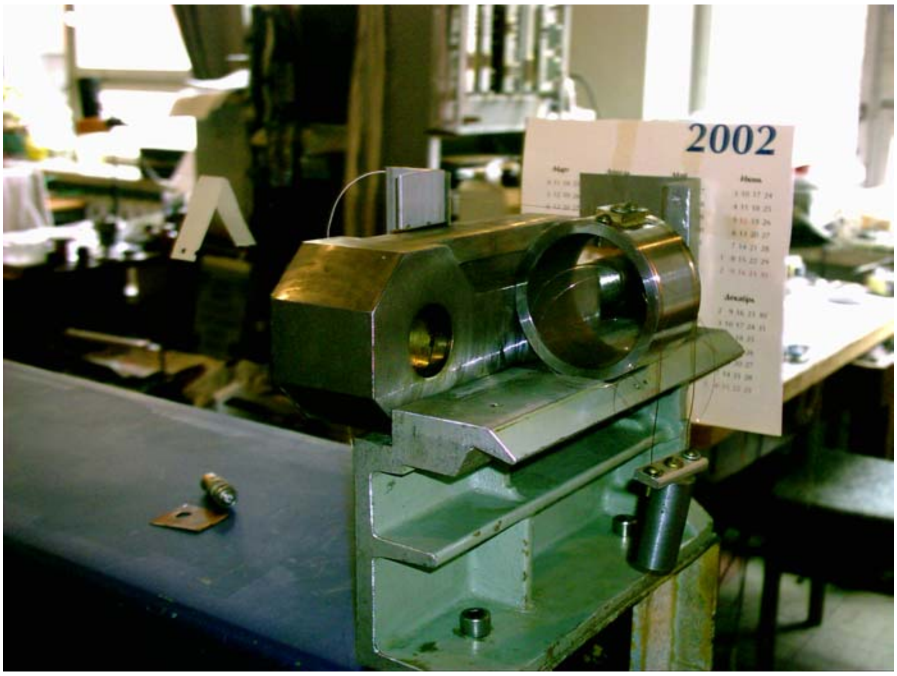


Fig.7. View of the stage with tensioned end of wire.

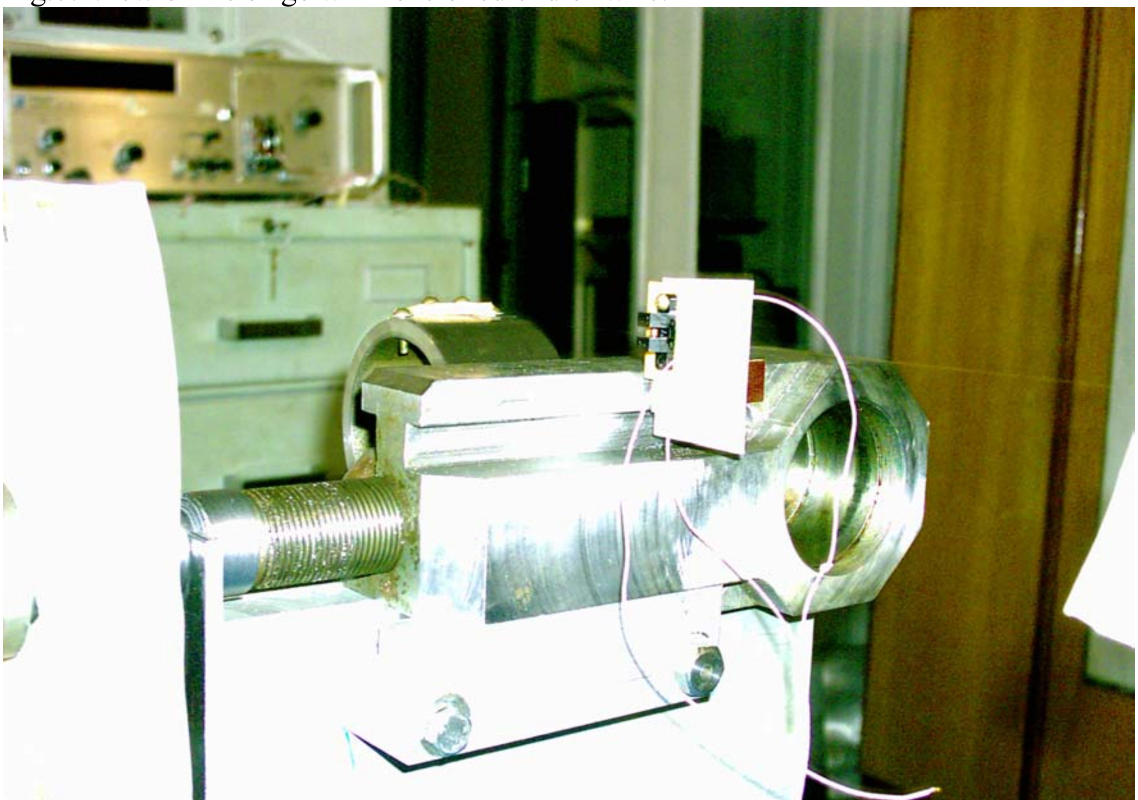


Fig.8. View of the stage with tensioned end of wire and optical sensor

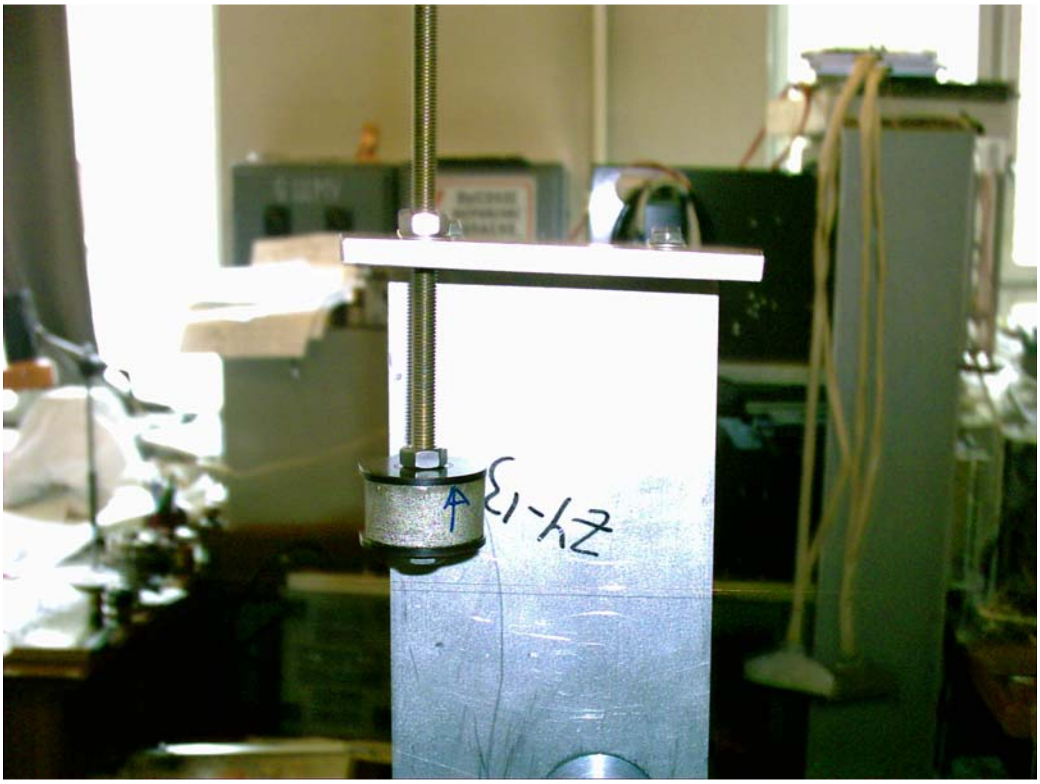


Fig.9. Ring PM for testing

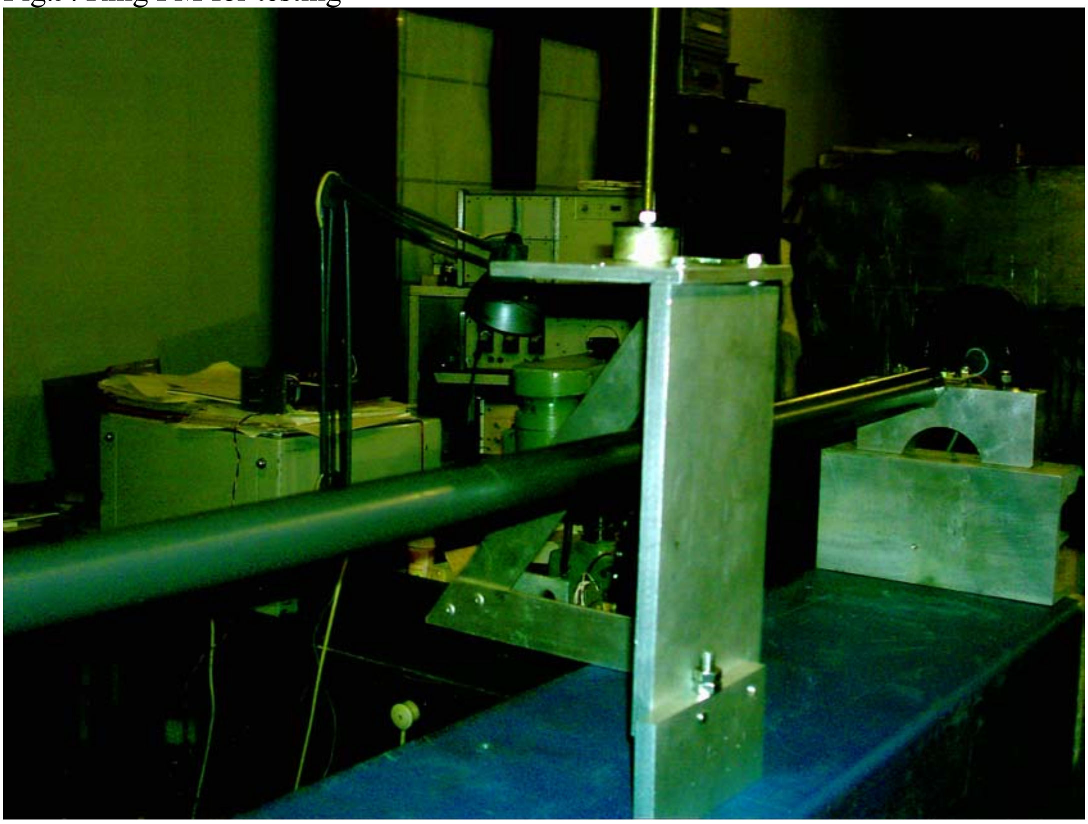


Fig.10. Tested PM and the wire enclosed into plastic tube

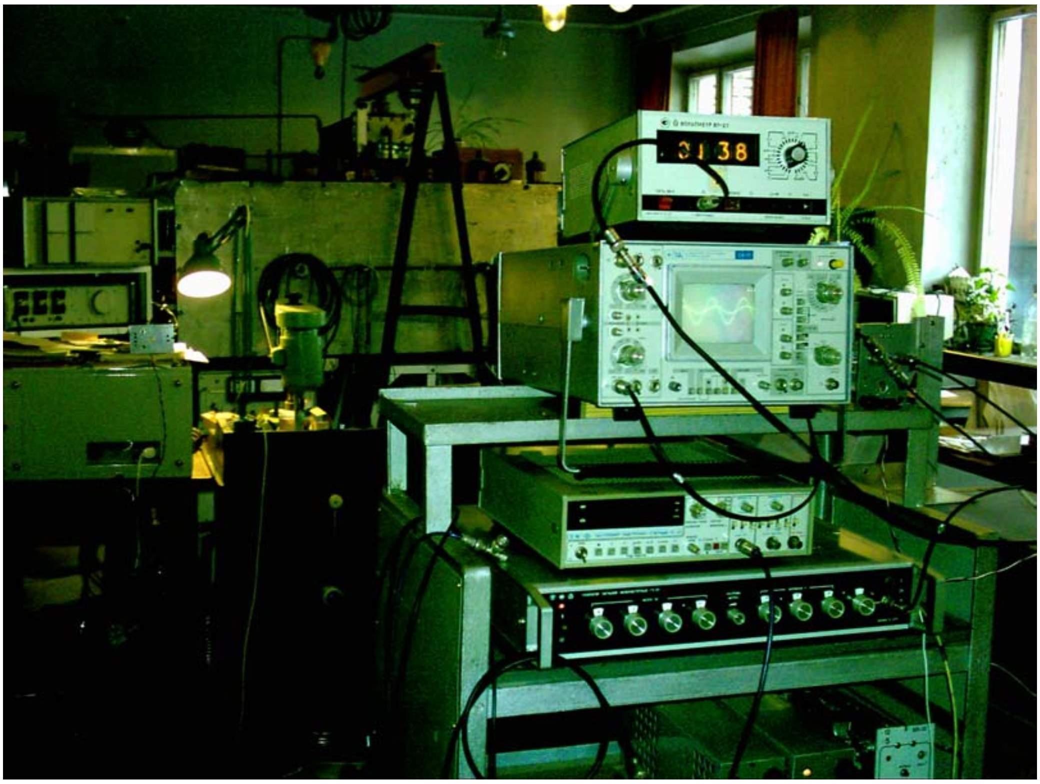


Fig.11.Rock with electronic equipment

Calibration of the optical sensor

A phototransistor-LED assembly was deployed as a wire position monitor. This kind of device was widely used in VWT and pulsed wire technique experiments. Fig.12 shows a schematic view of the assembly with the wire inside and electrical system surrounding it.

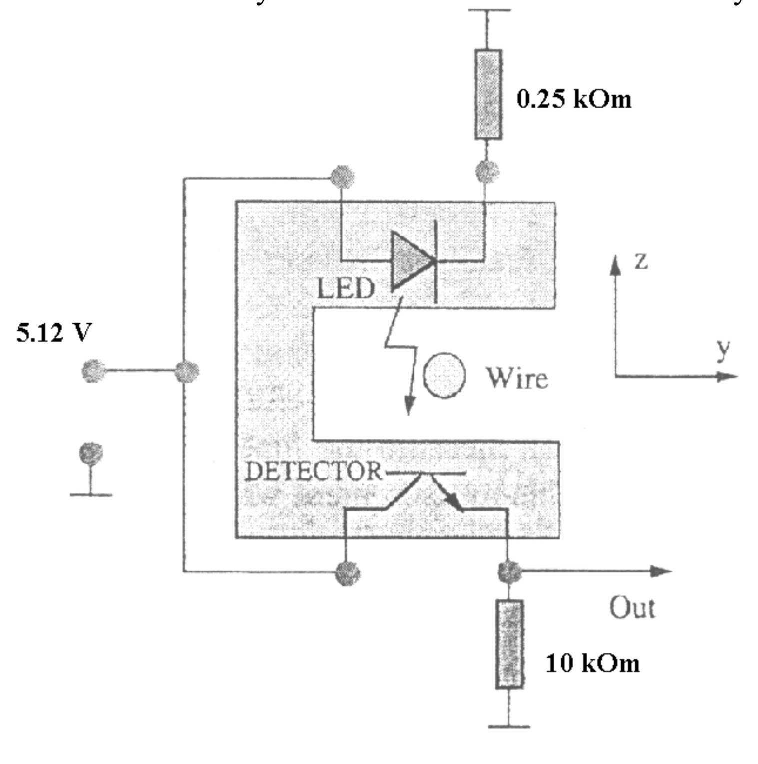


Fig.12.Schematic view of the optical sensor used as a wire position detector (cross-section)

For determination the detector sensitivity it's signal versus the wire position was measured. The changing of the detector position was realized by special screw. The experiments have shown that the sensitivity of the assembly is rather low (0.024 mV/μm) in case of use of the wire itself (Fig.13-14). It means that the wire diameter 0.19 mm was not enough to mask the suitable amount of the light flux. For increasing the detector sensitivity we have locally put on the wire the pieces of isolation of the various diameter. It was found that the element with diameter 1.2 mm can fully close the light flux. Finally we have used the element with diameter 0.85 mm which gives the detector sensitivity 14 mV/μm (Fig.15-16).

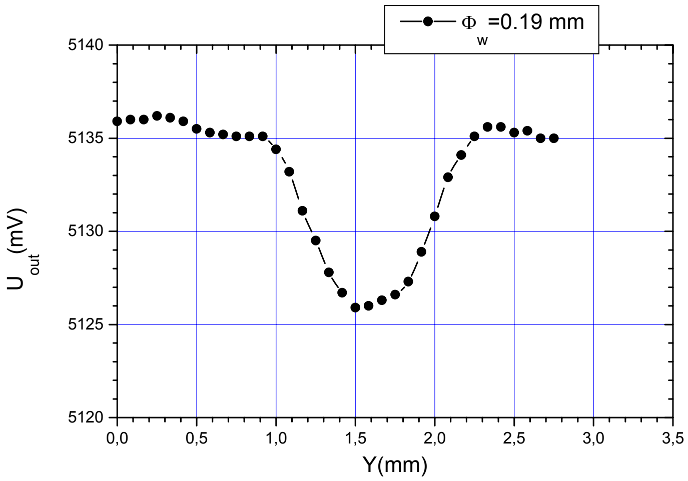


Fig.13. Position sensor signal versus horizontal wire position ($\varnothing_{wire}$=0.19 mm)

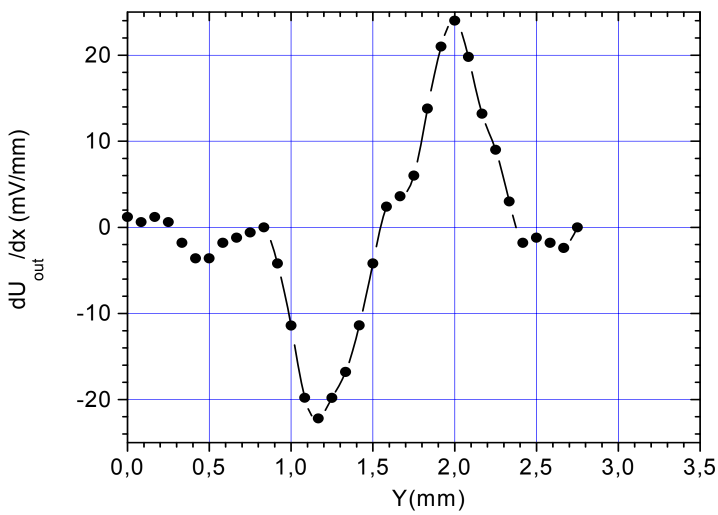


Fig.14. Derivative of the sensor signal ($\varnothing_{wire}$=0.19 mm)

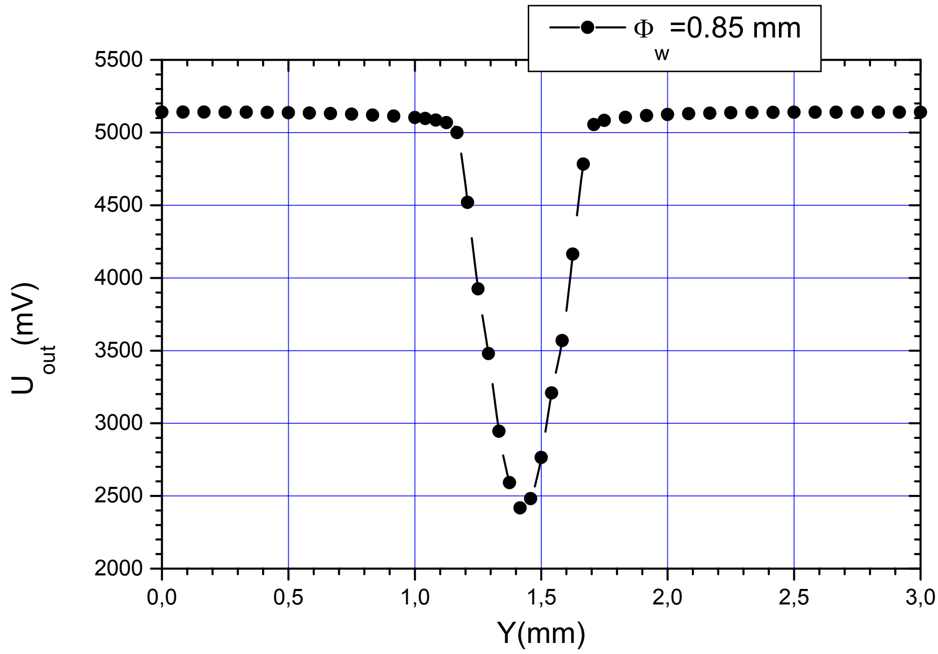


Fig.15. Position sensor signal versus horizontal wire position ($\varnothing_{element}$=0.85 mm)

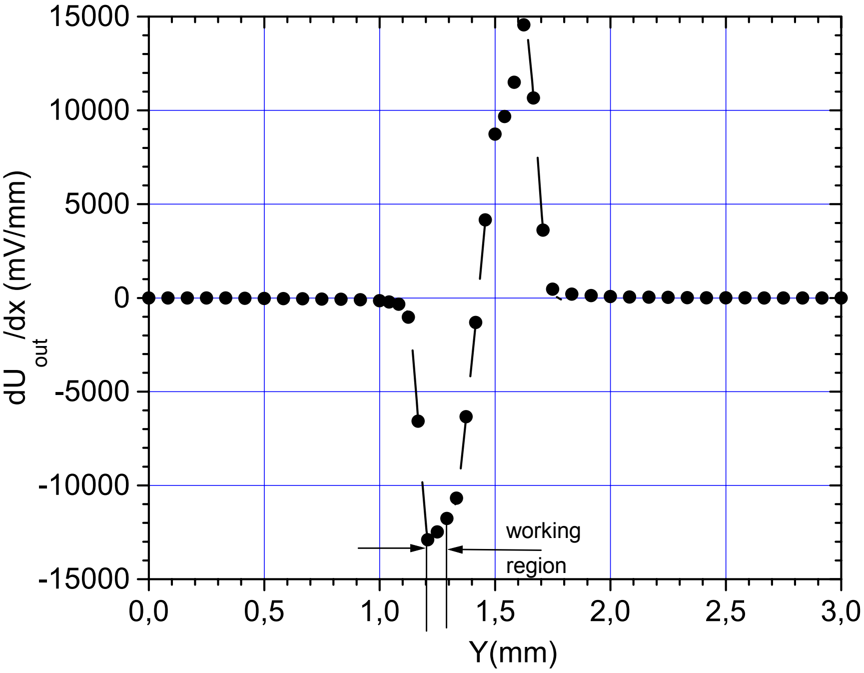


Fig.16. Derivative of the sensor signal ($\varnothing_{element}$=0.85 mm)

The working position of the sensor was tuning into the middle point of the linear part of the sensitivity curve (V_{out}=3.75 V). The working wire motion region for the sensor assumed to be ±0.05 mm, that was equal to ±0.65 V voltage region.

Magnetic field measurements for the test magnet

For the first test measurements the small ring permanent magnet was placed at the distance H_m= 50 mm from the wire. Fig.17 shows the magnetic field distribution for this magnet have been measured by the Hall probe and calculated by the POISSON code. The magnetic field integral along the wire direction (calculation by POISSON code) versus the distance between the test PM magnet and the wire is presented in the Fig.18. The Hall measurement is pointed in this Fig. by the cross.

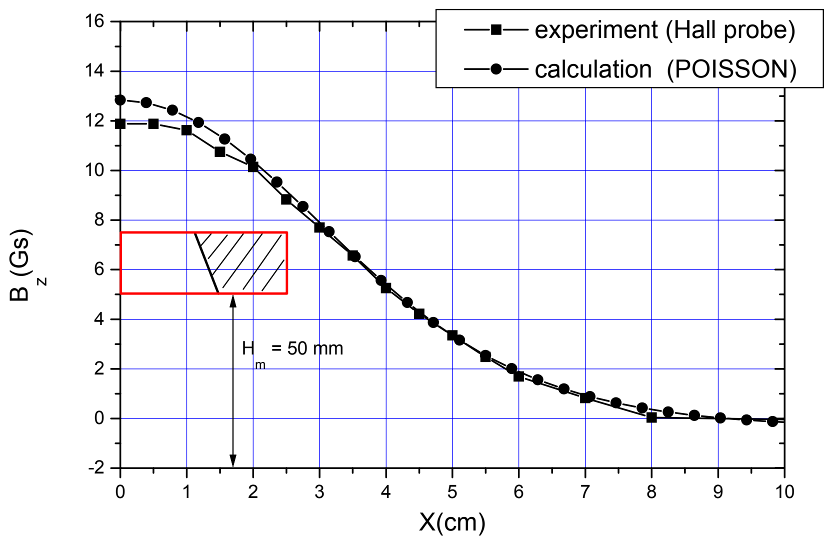


Fig.17. Magnetic field of the test PM magnet

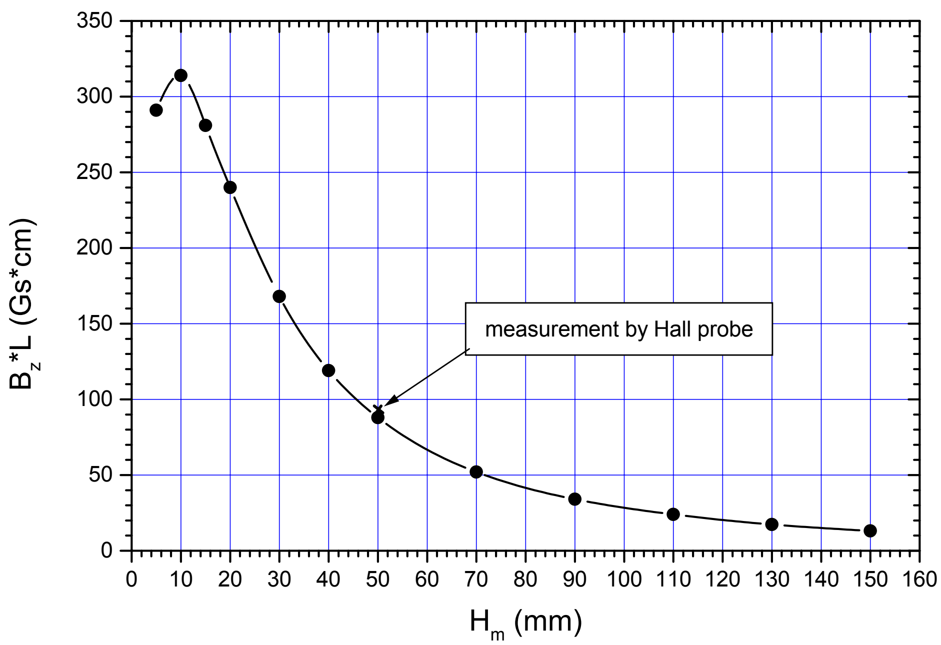


Fig.18. Magnetic field integral for the test PM magnet (calculation by POISSON)

The test magnet field Fourier transformation (at the wire length L_w=2.55 m) is shown in Fig.19 (black column). The test magnetic field restored from the Fourier harmonics is presented in Fig.20 and the tolerance of the magnetic field integral reconstruction versus the number of harmonics is presented in Fig.21. From this Fig. it is clear that the tolerance of the field integral reconstruction by first 5 harmonics is equal 2%.

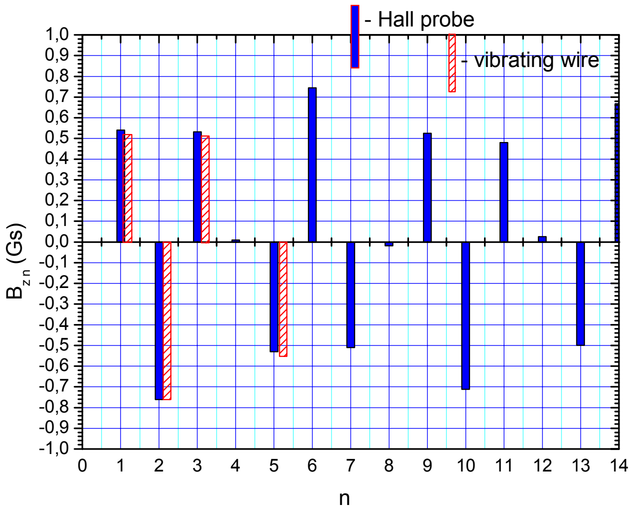


Fig.19. Harmonic components B_n calculated from Hall probe and vibrating wire measurements

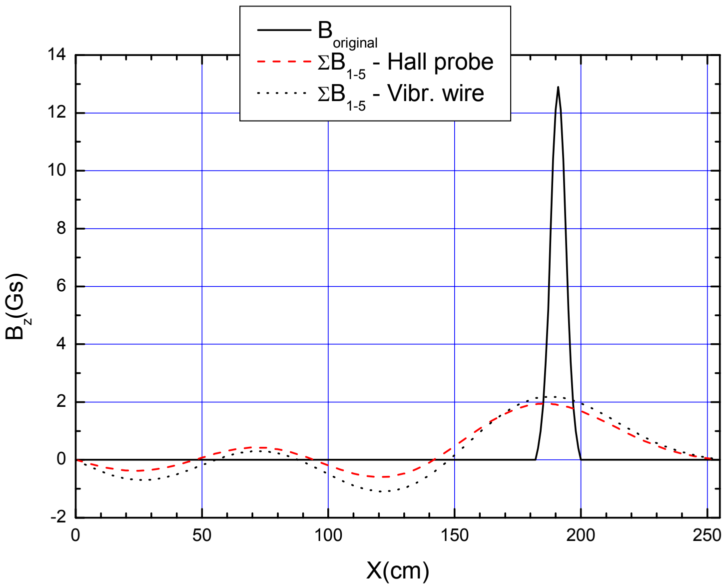


Fig.20. Restored magnetic field by 1 – 5 harmonics (B_n calculated from Hall probe and vibrating wire measurements)

The test PM field measurements by the VWT were realized in two steps. At the first one the measurement of the background magnetic filed was provided. At the second step – the measurement of the test magnet plus background field. The pure magnetic field of the test magnet was estimated as the difference between two measurements. Plot in Fig.22 show the results of excitation of the first harmonic for the background field measurement. Points show the measured function F(ω) defined in the theoretical section of the report [4]. Line in this Fig. is the fitting of the experimental points by special function defined in [4] too. The fitting function gives the possibility of calculation of the associated magnetic field harmonic. The values of the harmonics for the background field are in Fig.23 and the magnetic field reconstruction is in Fig.24.

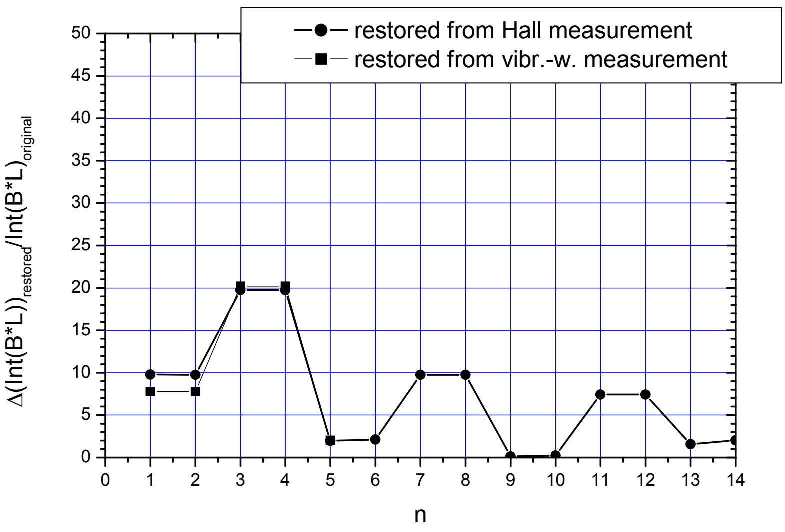


Fig.21. Tolerance of the magnetic field integral reconstruction

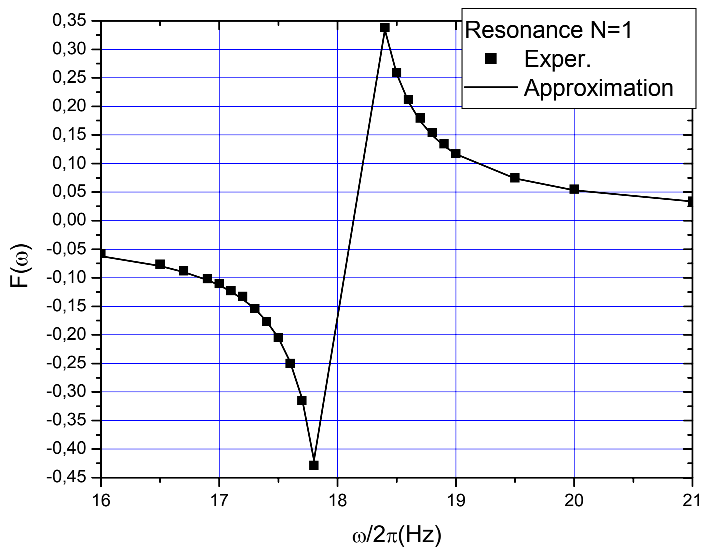


Fig.22. Function F(ω), N=1 (background field)

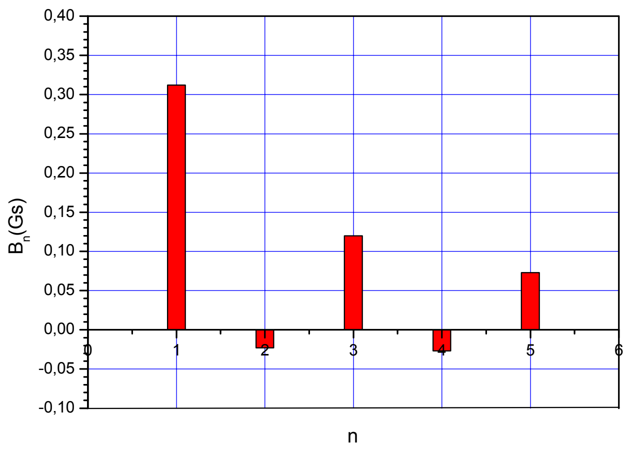


Fig.23. Harmonic components B_n for the measured background magnetic field

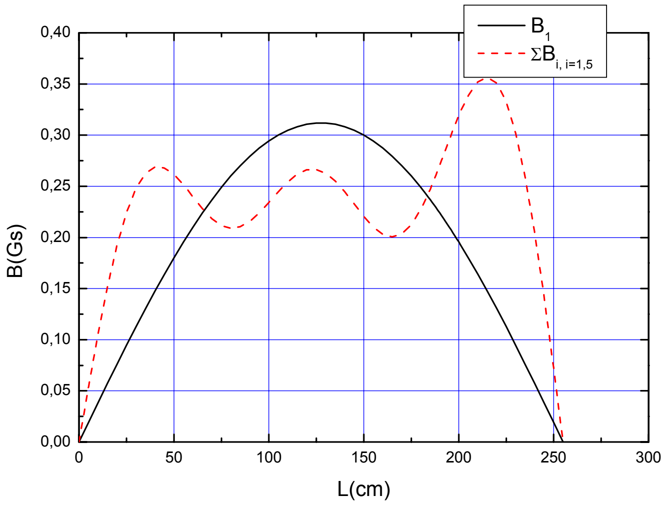


Fig.24. Restored magnetic field by 5 harmonics for the background

The magnetic field harmonics calculated from the measurement for the test PM and the tolerance of magnetic field integral reconstruction is shown in Fig.19-21. The same measurements by VWT were provided for the test magnet distance from the wire H_m=96 mm. All results are summarized in Tab.3.

Table 3. VWT test measurements

	VWT Background	Hall probe (H_m=50 mm)	VWT (H_m=50 mm)	VWT (H_m=96 mm)
Harm. number	B_n(Gs)	B_n(Gs)	B_n(Gs)	B_n(Gs)
1	0.312	0.541	0.553	0.184
2	-0.023	-0.761	-0.758	-0.379
3	0.120	0.531	0.504	0.234
4	-0.027	0.009	-0.048	-0.013
5	0.073	-0.531	-0.552	-0.306
∫B*dx (Gs*cm)	59.45	97.3	99.26	32.69 (31.6 POISSON)
Tolerance (Gs*cm)			2.04	1.09

The data of the Tab.3 shows that the tolerance of the VWT field integral measurement is 2-3% for the field integral 100-30 Gs*cm.

4. Expectation on spectrometer magnet "zero" field measurement using VWT

Suggestion that the spectrometer magnet "zero" field has to have the value 10^{-5} of the working field integral means 1.5 Gs*cm for minimal spectrometer energy (45 GeV) and 13.3 Gs*cm for the maximal one (400 GeV). It this possible to measure the spectrometer magnet field directly. The above experiments with VWT show the accuracy about 1-2 Gs*cm in case of the absolute measurement of the field integral. We suggested to modify a little the VWT and to use it in the relative way. If to provide the Fourier transformation of the spectrometer magnet field it is possible to see that the harmonic number one has the prevailing value. In Fig.25 the results of the Fourier transformation (at the length 6 m) for the normalized magnet field are presented. In Fig.26 the normalized spectrometer magnet field and the restored ones by the different numbers of harmonic are shown. Fig.27 shows the accuracy of the magnet field integral reconstruction using the different number of harmonics. From the last Fig. it is clear that using the harmonic number one only we can get 86% of the magnet field integral. It means that to obtain the zero position on the magnet excitation line one should measure the detector signal from the vibrating wire versus the current in magnet coil keeping the wire driving current frequency as close as possible to the mode frequency N=1 . The accuracy of such measurement on zero field location directly depends from the level of the detector signal. The experiments with the test magnet shows that in the field 10 Gs*cm the level of the detector signal is 100 mV. The suggestion of the 1 mV accuracy of the detector signal measurement means the 0.1 Gs*cm accuracy of the "zero" field finding. The results of such way measurement for crossing zero field by rotating the test PM is in Fig.28. "Zero" field measurement and adjustment requires special low current magnet power supply. It maximal current depends from the level of the remanent magnetic field (if 1 Gs – 0.06 A). The accuracy of this current excitation is about 10^{-4}, the minimal current step 10^{-4} A.

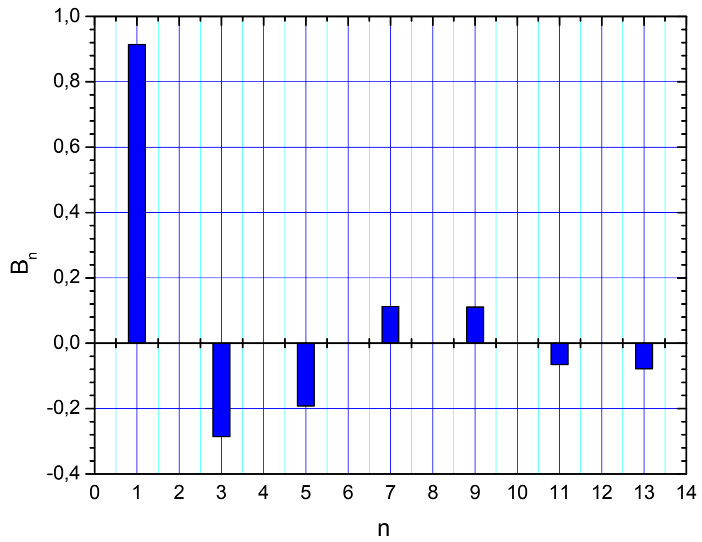


Fig.25. Harmonic content for the spectrometer magnet magnetic field

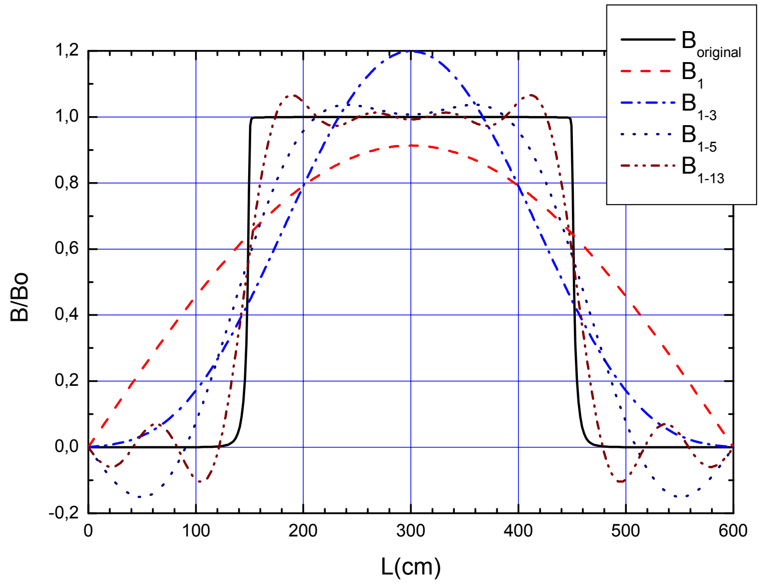


Fig.26. Magnetic field restored from the harmonics

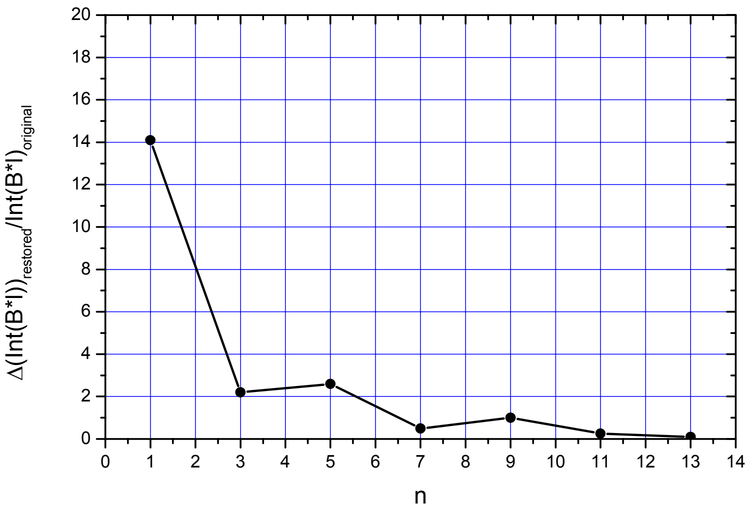


Fig.27. Accuracy of the magnetic field integral reconstruction

The final decision about what type of method is most suitable for 'zero' field determination mainly depends from real shape of the residual magnetic field distribution. It means that a volume of experimental works is required on determination of low level residual field for some test magnets.

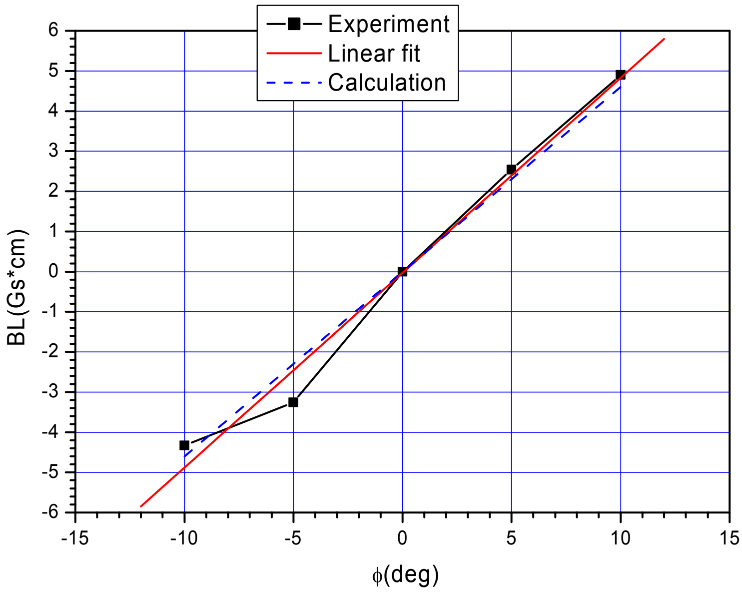


Fig.28. Crossing zero field by rotation of the test PM

Conclusions

1. The NMR and Hall magnetometers were manufactured, tested and calibrated.
2. It was proposed to use the fluxgate magnetometer and vibrating wire technique for 'zero' field measurements.
3. The test bench to check the possibilities of vibrating wire technique was created and commissioned.
4. A first set of experiments on magnetic field measurements were provided. It was approved the utility of VWT for the low level magnetic field measurements.
5. The accuracy of magnetic field integral measurement was 2-3% in range of 30-100 Gs*cm.
6. It is proposed to use for "zero" field finding the excitation of the vibrating wire at the mode frequency N=1 and the measuring the point of zero signal changing the excitation of the magnet current. The suggested accuracy of "zero" magnetic field finding is about 0.1 Gs*cm.
7. A special low current power supply is required for "zero" field adjustment.
8. For the direct check of this accuracy the experiments for some test magnets on zero magnetic field measurements have to be realized.

References

[1] JINR News, 1, 2005, Dubna.
[2] A.Temnykh – Vibrating wire field-measuring technique, Nucl. Instr., A 399 (1997), 185-194.
[3] A.Temnykh – Vibrating wire field-measuring technique, Preprint CBN 96-7.
[4] A.Temnykh – The magnetic center finding using vibrating wire technique, Preprint CBN 99-22.