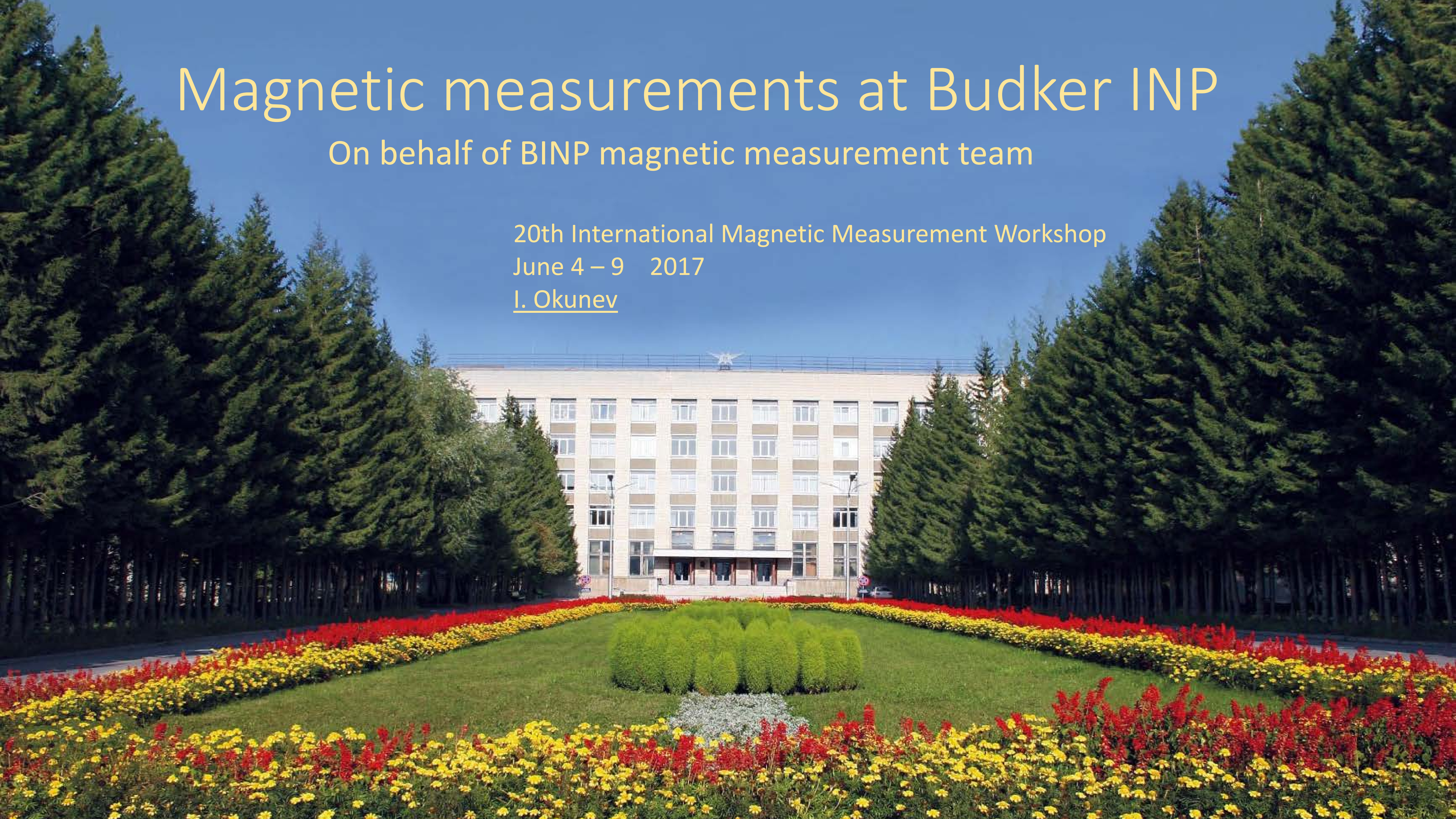
Magnetic measurements at Budker INP

On behalf of BINP magnetic measurement team

20th International Magnetic Measurement Workshop
June 4 – 9   2017

I. Okunev



Budker Institute of Nuclear Physics

Siberian Branch of Russian Academy of Science

- Basic research activity
  - High energy physics and e^+e^- colliders
  - Accelerator physics and technology
  - Thermonuclear research
  - Theoretical physics

Applied research activity

- Synchrotron radiation and FEL
- Industrial accelerators
- Physics for medical application
- Accelerator mass spectrometer

Development and design

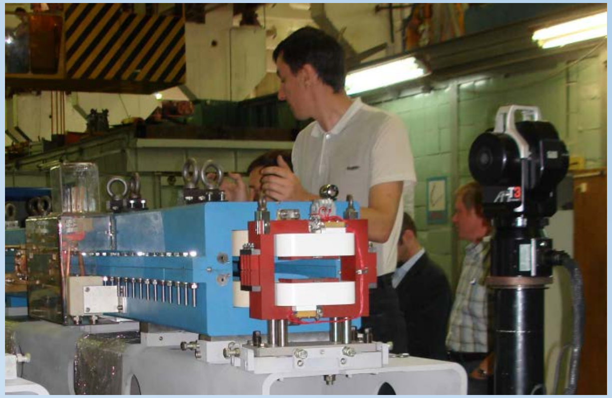
- Experienced scientists can develop any (new) product required by customer from scratch
- A Design Department (100 designers) is equipped with the modern CAD software (AutoCAD, Solid Edge, Inventor, SolidWorks, Cati)
- BINP designers are familiar with design standards, tools, procedures of CERN, DESY, BESSY, etc.

The Experimental Workshop

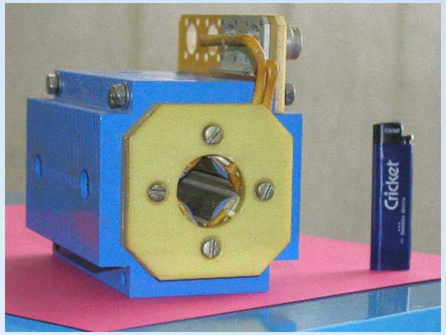
- Comprises 150 technological divisions, sectors and specialized shops placed on the three production areas (~ 60 000 m²). About 700 of workers, technologists and engineers work in Workshop.
- ISO 9001:2008 certificate Bureau Veritas
- ГОСТ ISO 9001-2011 и ГОСТ РВ 0015-002-2012 (Russia)
- Certificates (TUV, BV, NACW) for welding shop, welders, inspection tests, technologists, etc.

Some magnet types fabricated by BINP

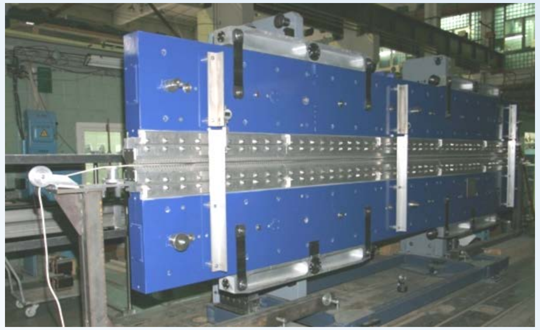
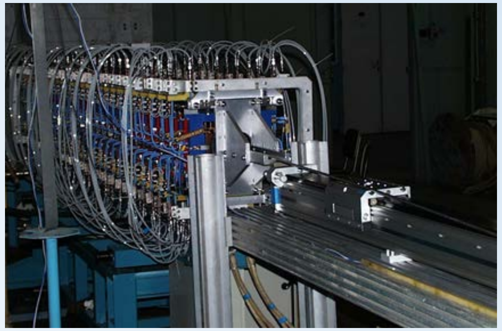


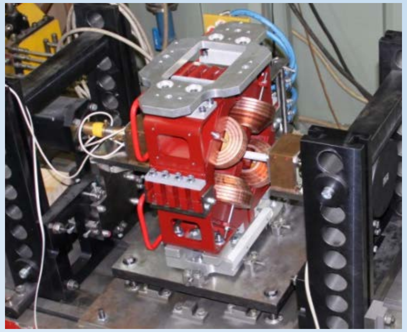










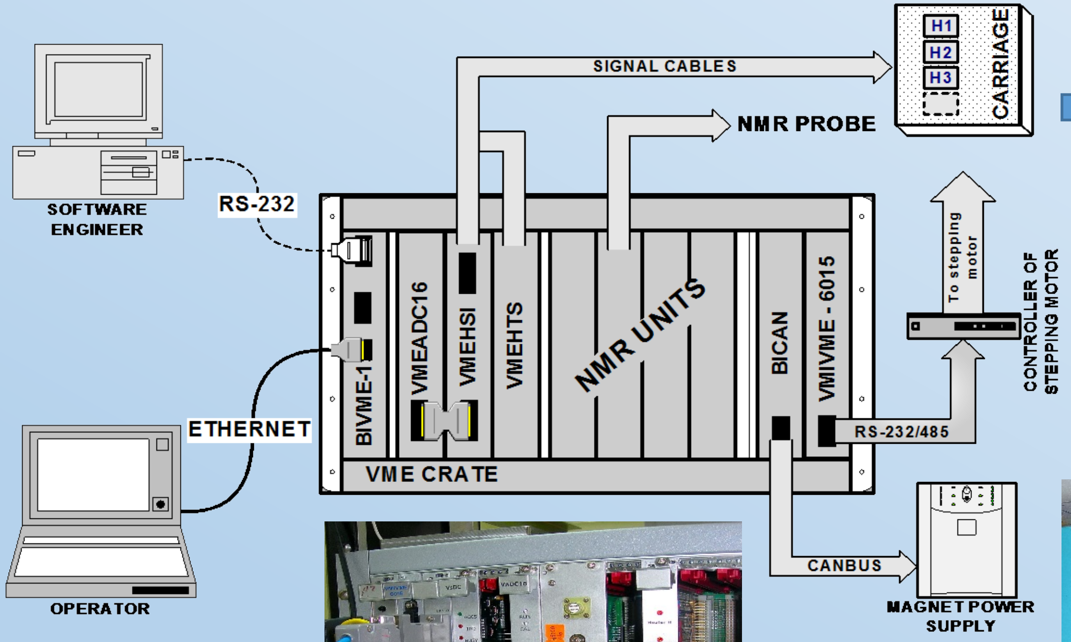

Magnetic measurement laboratory

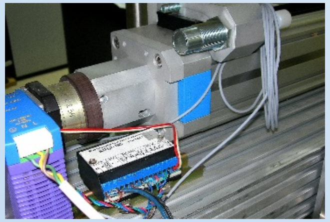
BINP has four setup for magnetic measurements

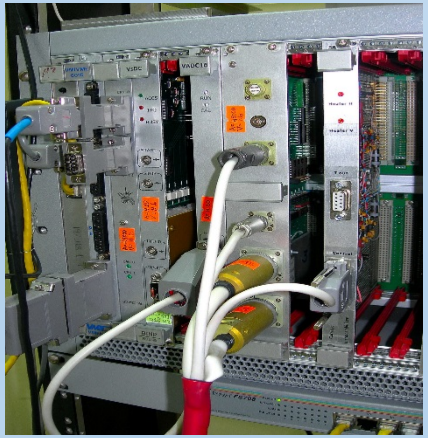
- One directly at the workshop
  1. Measurements by Hall sensors, NMR and rotating coils
- Three at the BINP
  1. Hall sensors, NMR, λ-coil, stretched wire
  2. Rotating coils, string - resonance method and direct current method, Hall sensor for measurements at a temperature of liquid helium
  3. Pulsed measurements using the induction method

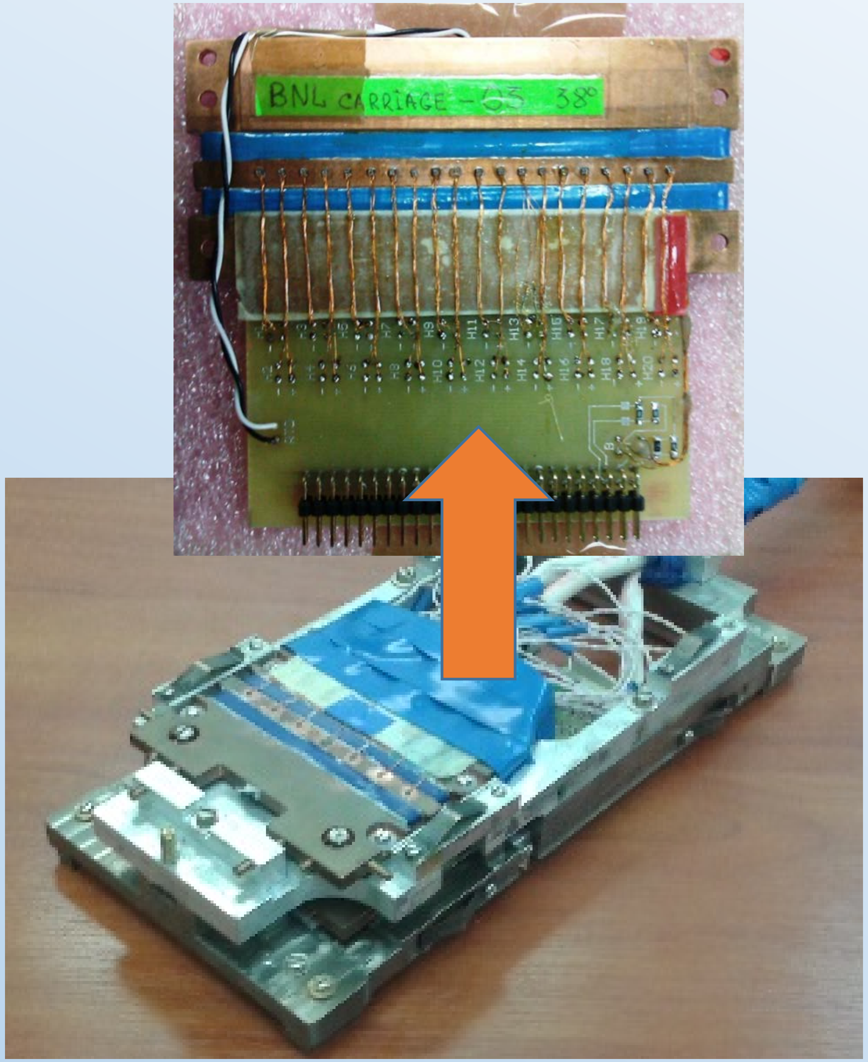
Hall probe and NMR systems

Hall probe system



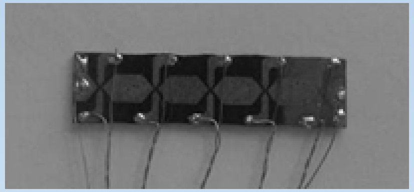
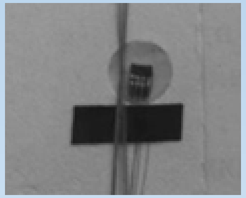
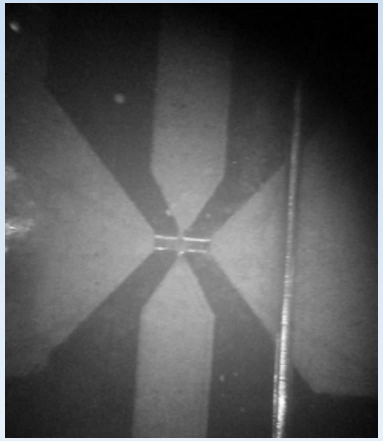
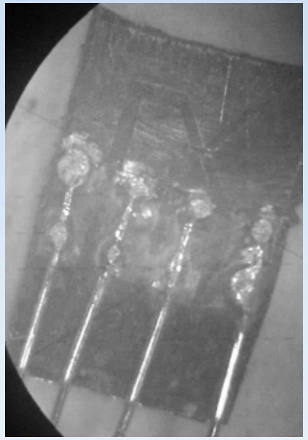




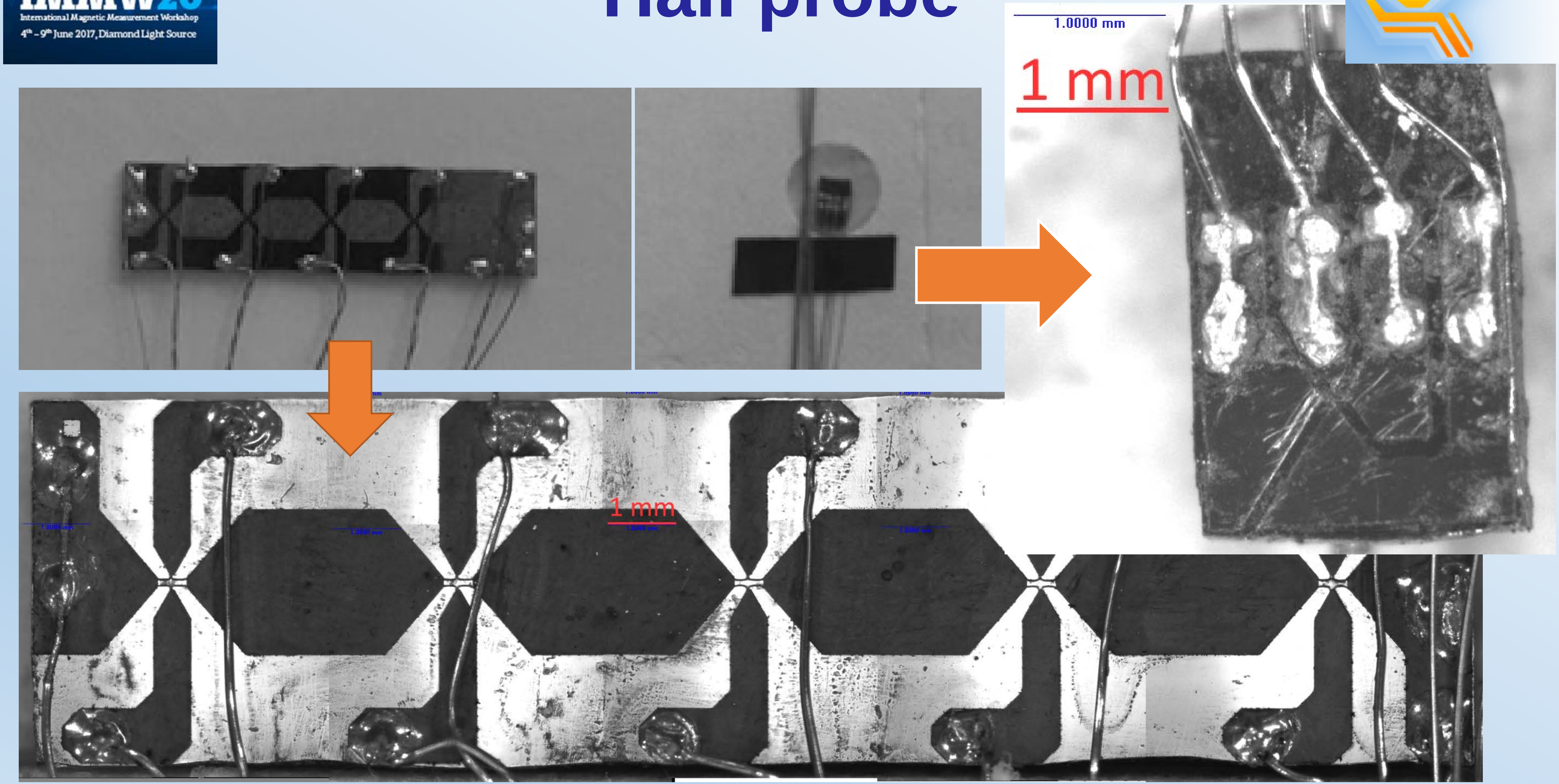


Hall probe

Converter dimensions, mm	3×2×0.6
Dimensions of the sensitive zone, mm	0.1×0.05
Input resistance, Ohm	9.8
Output impedance, Ohm	14.2
Residual voltage, µV	45
Magnetic sensitivity at B = 0.1 T, µV / mT	119.6
The coefficient of nonlinearity at B = 2.0 T,%	–
The divergence coefficient at B = 0.1 T,%	0.07
Temperature coefficient of sensitivity, %/°C	–0.006
Temperature coefficient of residual voltage, µV / ° C:	–0.6
Supply current, mA	100
Operating temperature range, K	1.5÷373

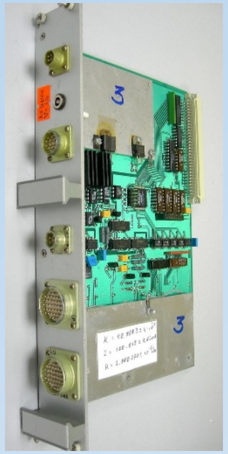
Hall probe



Measuring and control electronics

Analog interface of Hall sensors

Number of channels	32 differential
Input Range	±250 mV
Common-mode signal range	до ±12 V
Preamplifier gain	40.000 ÷ 40.002
Drift	±1ppm/C°
Noise brought to the entrance	2μV/digit
Drift of zero displacement	±30 nV/C°
Sensor operating current	99.996±0.001 mA
Current drift	±2ppm/C°
Dimensions	2M VME

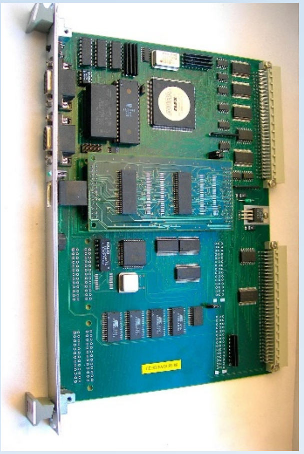


Control electronics

Controller BIVME-1
Description:

CPU	**Motorola MC68EN360**
Frequency	**32 MHz**
RAM	**32-bit, 8 /16 Mbytes**
ROM	**128 Kbytes Boot ROM**
Flash memory	**8 Mbytes**

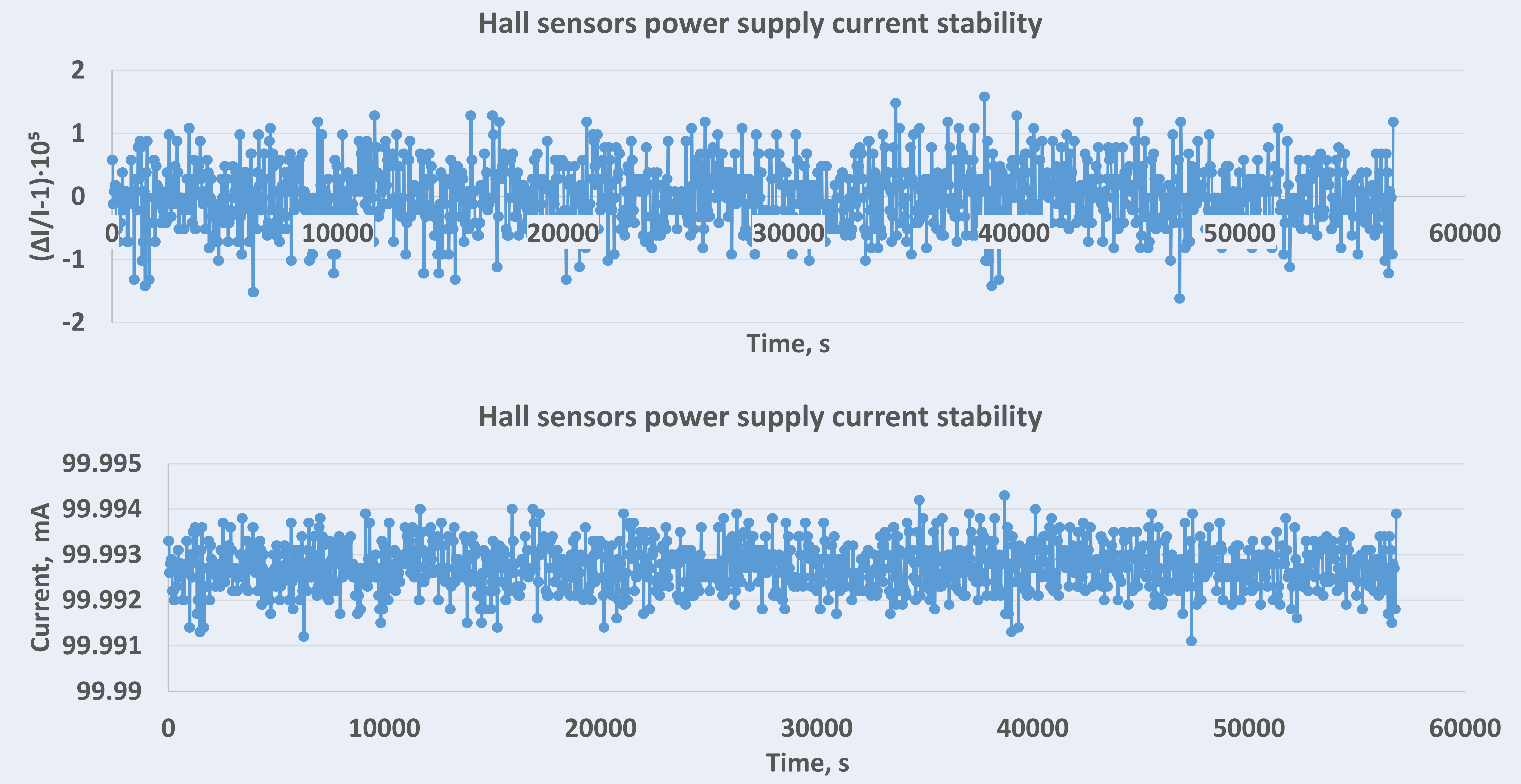
I/O ports 2: RS-232, 1: Ethernet 10base-T

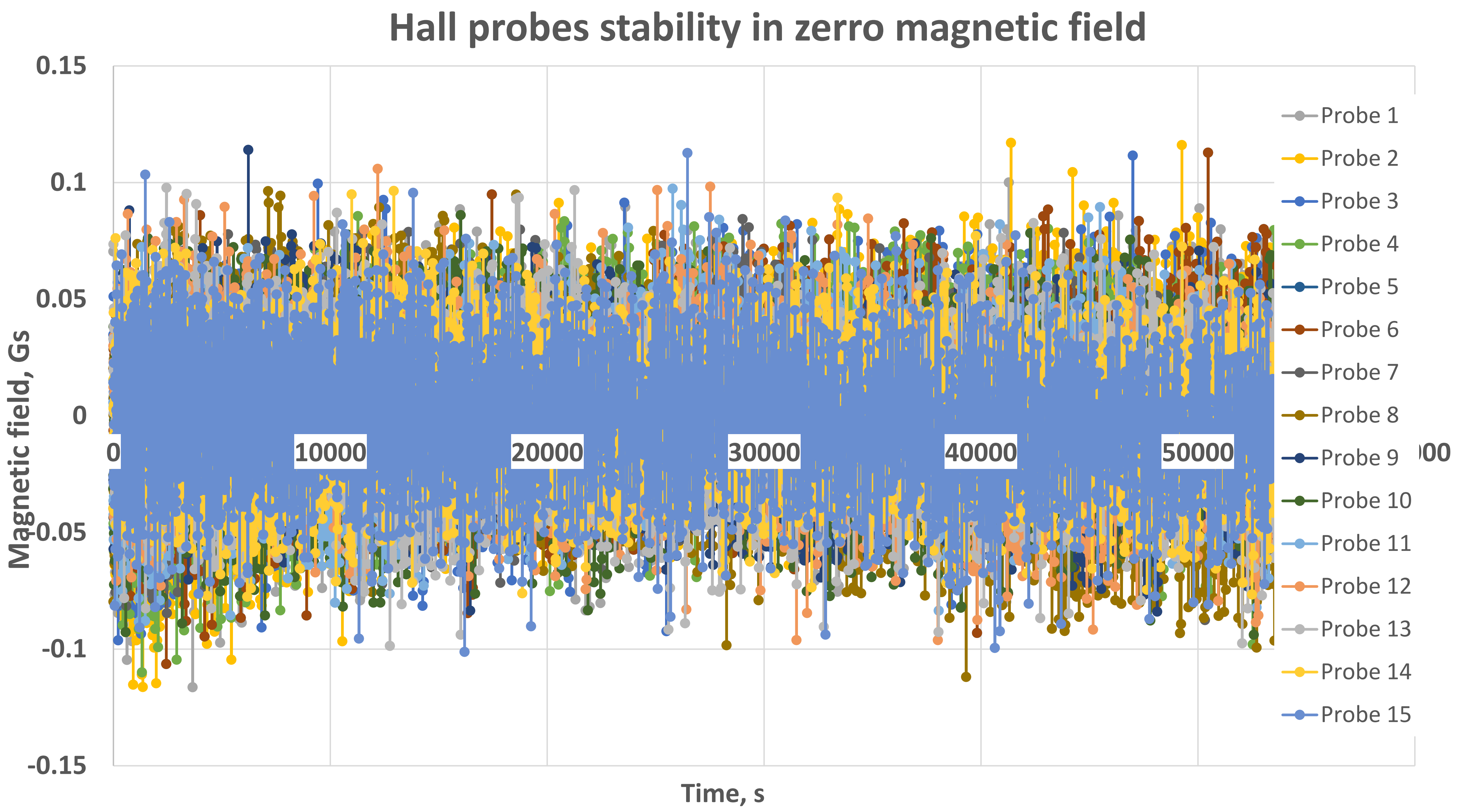


Basic parameters of ADC

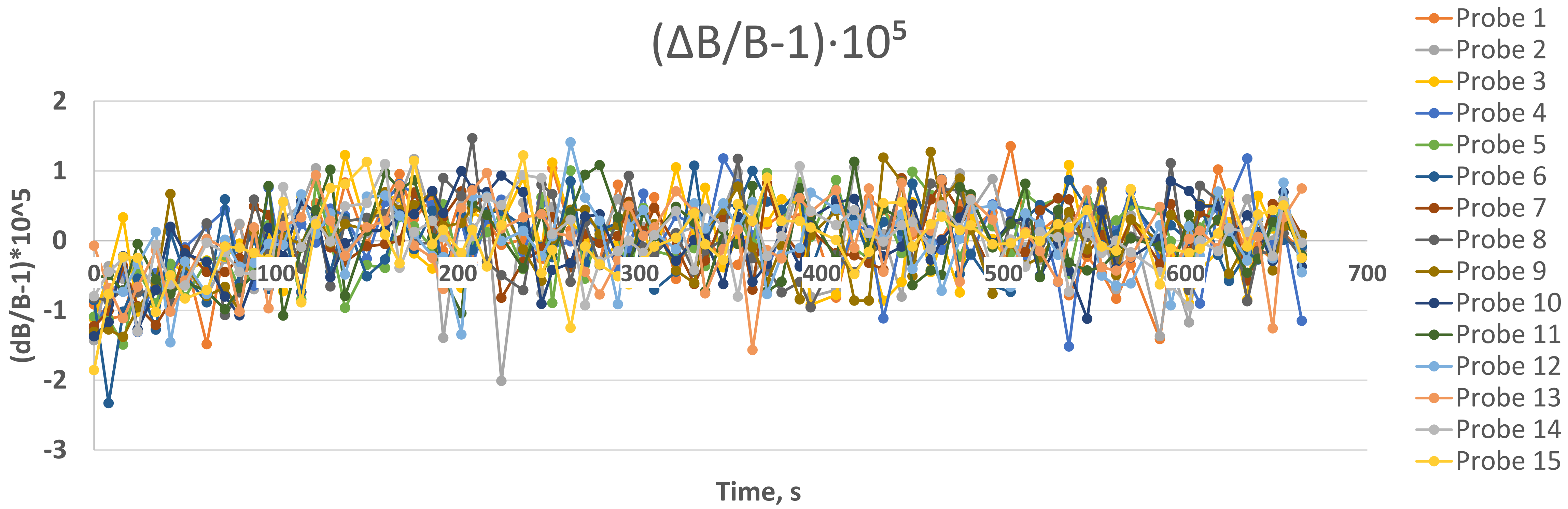
Resolution	23 bit
Effective bits @ 20ms	20 bit
Input Range	±10 V
Accuracy @ 20°÷ 50°	0.003%
Zero offset	±20 μV
Noise @ 20ms	40 μV/digit
Intervals between measurements	5,10,20,40,80,160 ms
Min Intervals between measurements when working with VMEHSI	80 ms
Dimensions	1M VME

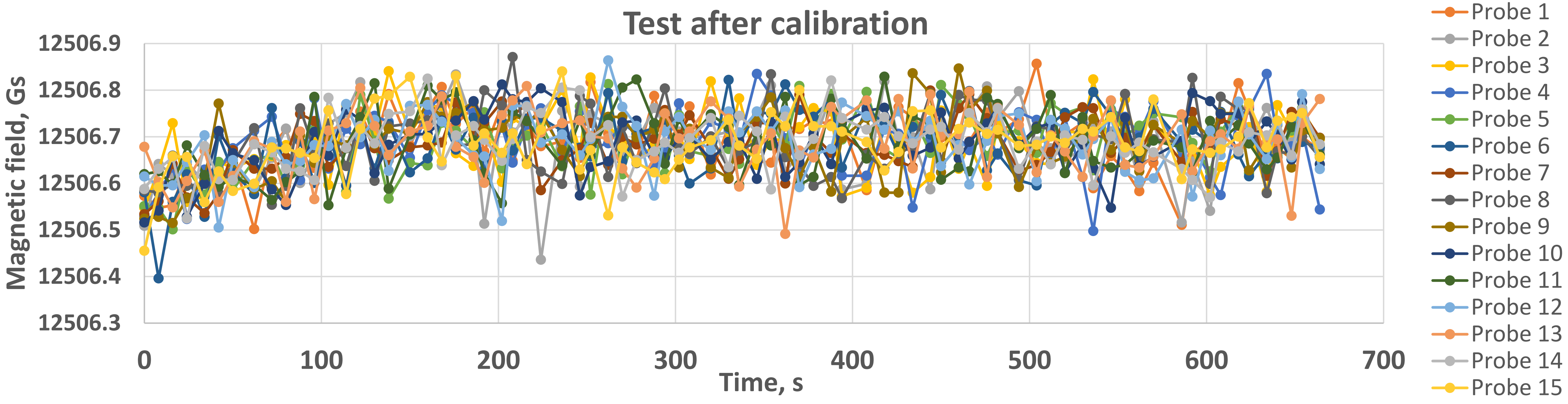
Hall probe stability

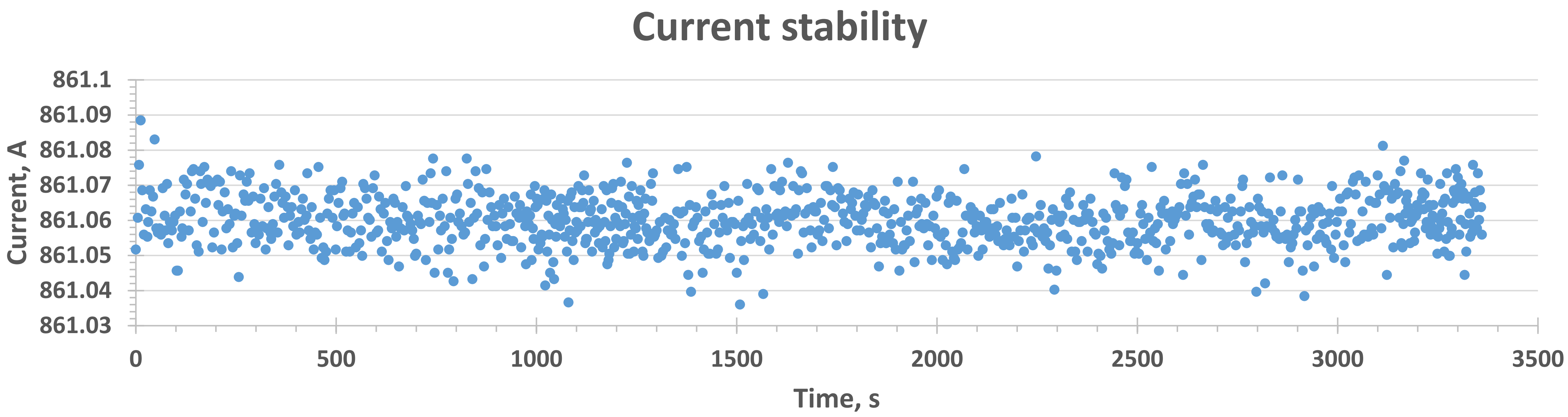


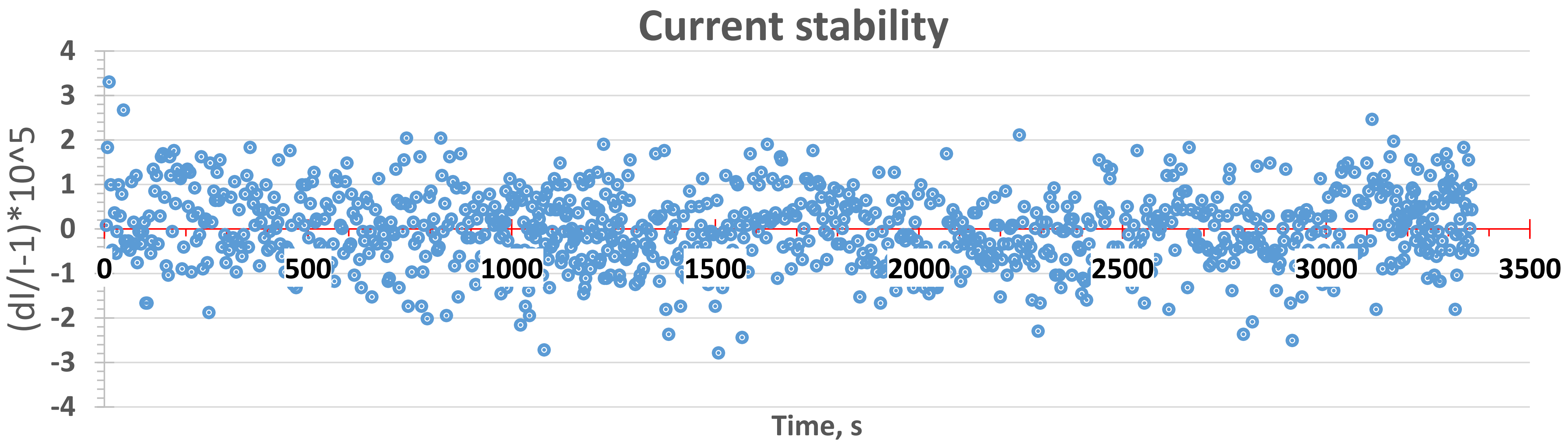


Hall probes stability in zerro magnetic field
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Magnetic field, Gs
0
10000
20000
30000
40000
50000
Time, s
Probe 1
Probe 2
Probe 3
Probe 4
Probe 5
Probe 6
Probe 7
Probe 8
Probe 9
Probe 10
Probe 11
Probe 12
Probe 13
Probe 14
Probe 15


(ΔB/B-1)·10^5
(dB/B-1)*10^5
Time, s
Probe 1
Probe 2
Probe 3
Probe 4
Probe 5
Probe 6
Probe 7
Probe 8
Probe 9
Probe 10
Probe 11
Probe 12
Probe 13
Probe 14
Probe 15


Test after calibration
Magnetic field, Gs
Time, s
Probe 1
Probe 2
Probe 3
Probe 4
Probe 5
Probe 6
Probe 7
Probe 8
Probe 9
Probe 10
Probe 11
Probe 12
Probe 13
Probe 14
Probe 15


Current stability
Current, A
861.1
861.09
861.08
861.07
861.06
861.05
861.04
861.03
0
500
1000
1500
2000
2500
3000
3500
Time, s


Current stability
(dI/I-1)*10^5
4
3
2
1
0
-1
-2
-3
-4
0
500
1000
1500
2000
2500
3000
3500
Time, s

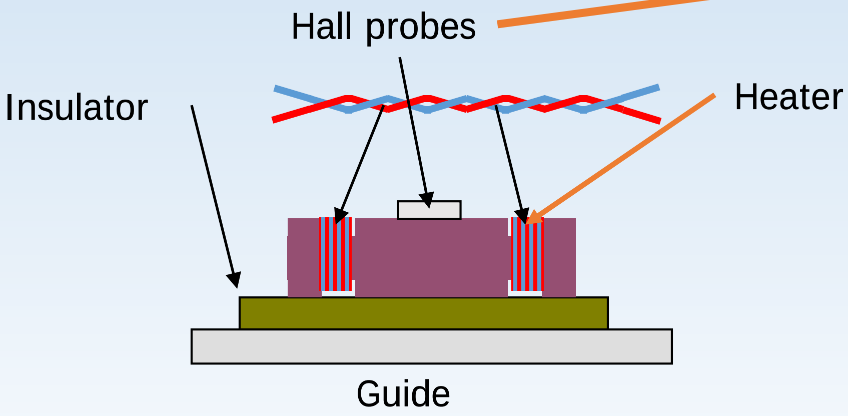
Temperature stabilization of the Hall sensors

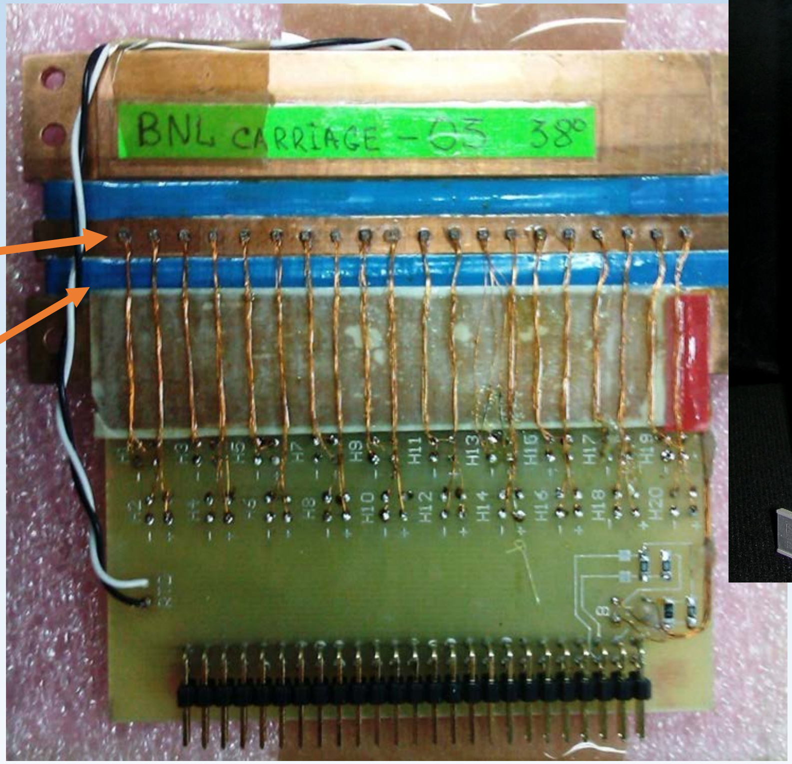
Thermostabilization

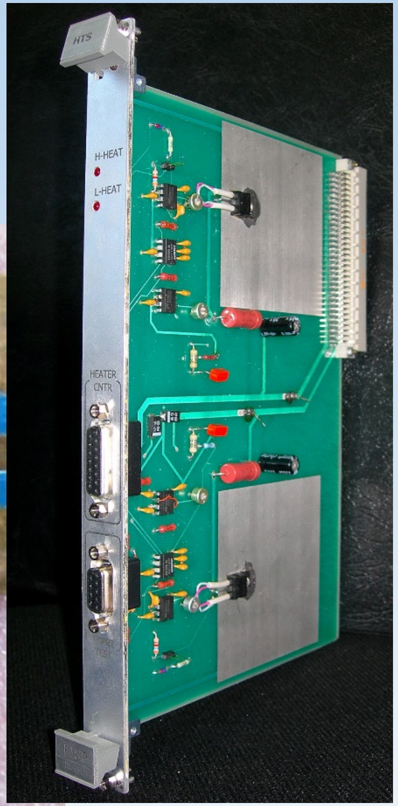
The copper base on which the Hall sensors are mounted is equipped with a heater and a temperature sensor for thermostabilization

Parameters

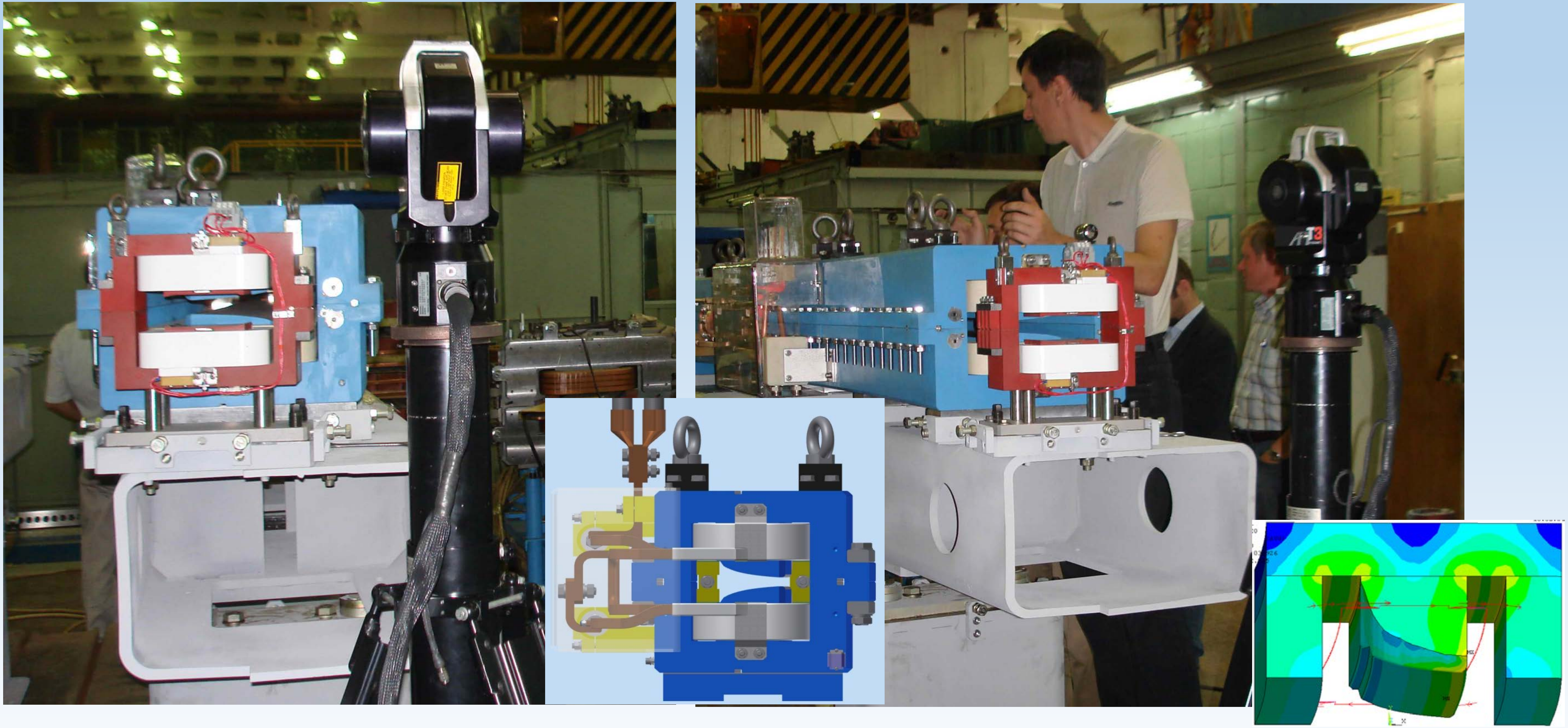
Temperature	**35° - 45° C**
Instability	**±0.3° C**
Maximum current	**0.6 A**







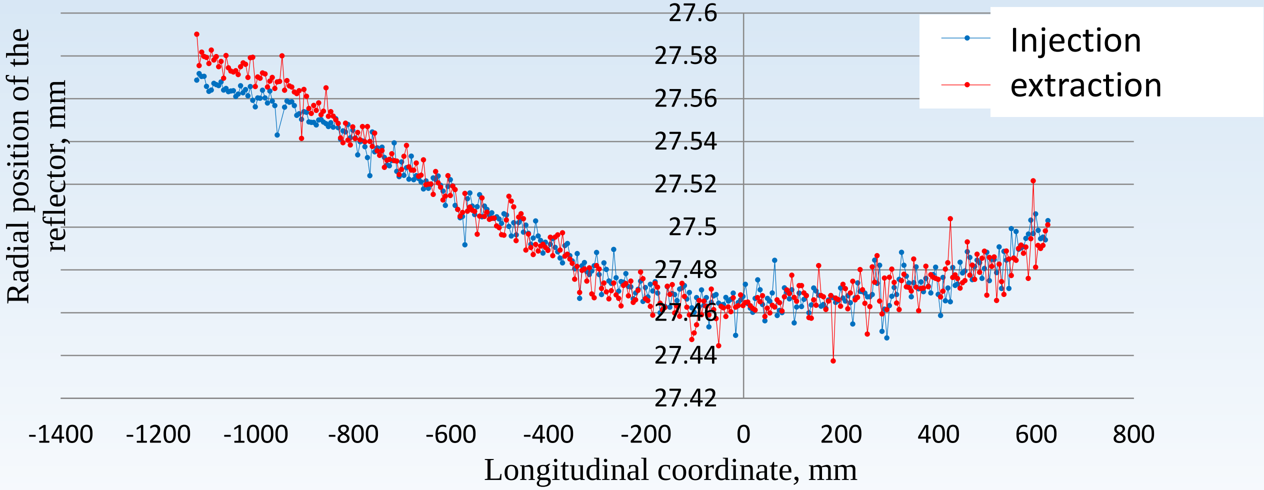
Coordinate measuring machines in magnetic measuring setup



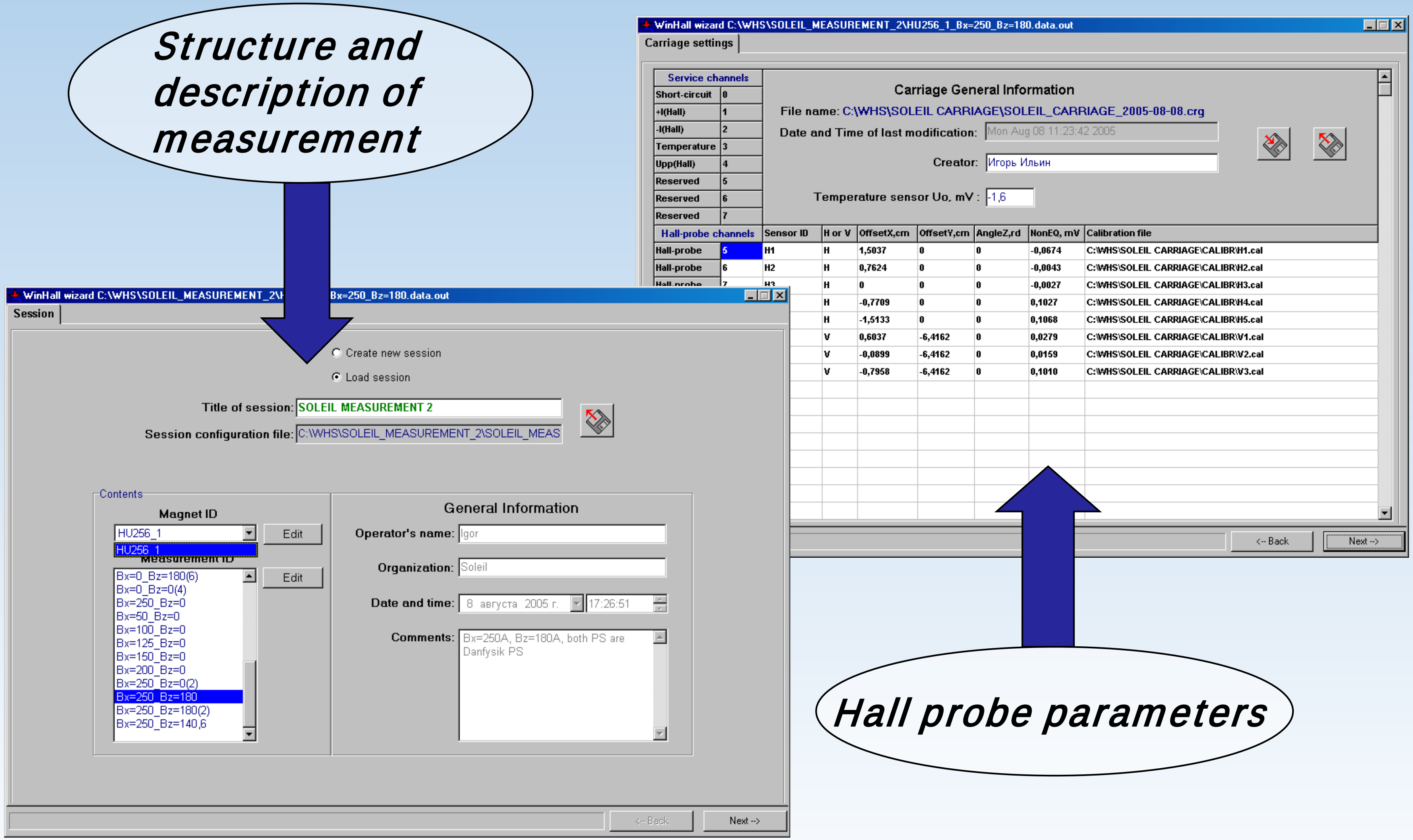
Coordinate measuring machines in magnetic measuring setup

Calibration procedure using the Laser Tracker and CMM - ZEISS Contura G2. This procedure allows you to bind the optical coordinates of the reflectors with position of the Hall sensors.

Example of measurement of the probes radial position using Laser Tracker. Coordinate system tied to fiducial target of the magnet



Software


Structure and description of measurement
Hall probe parameters
WinHall wizard C:\WHS\SOLEIL_MEASUREMENT_2\HU256_1_Bx=250_Bz=180.data.out
Carriage settings
Service channels
Carriage General Information
File name: C:\WHS\SOLEIL CARRIAGE\SOLEIL_CARRIAGE_2005-08-08.crg
Date and Time of last modification: Mon Aug 08 11:23:42 2005
Creator: Игорь Ильин
Temperature sensor Uo, mV : -1,6
Hall-probe channels
Session
Create new session
Load session
Title of session: SOLEIL MEASUREMENT 2
Session configuration file: C:\WHS\SOLEIL_MEASUREMENT_2\SOLEIL_MEAS
Contents
Magnet ID
HU256_1
Measurement ID
Edit
General Information
Operator's name: Igor
Organization: Soleil
Date and time: 8 августа 2005 г. 17:26:51
Comments: Bx=250A, Bz=180A, both PS are Danfysik PS
<-- Back
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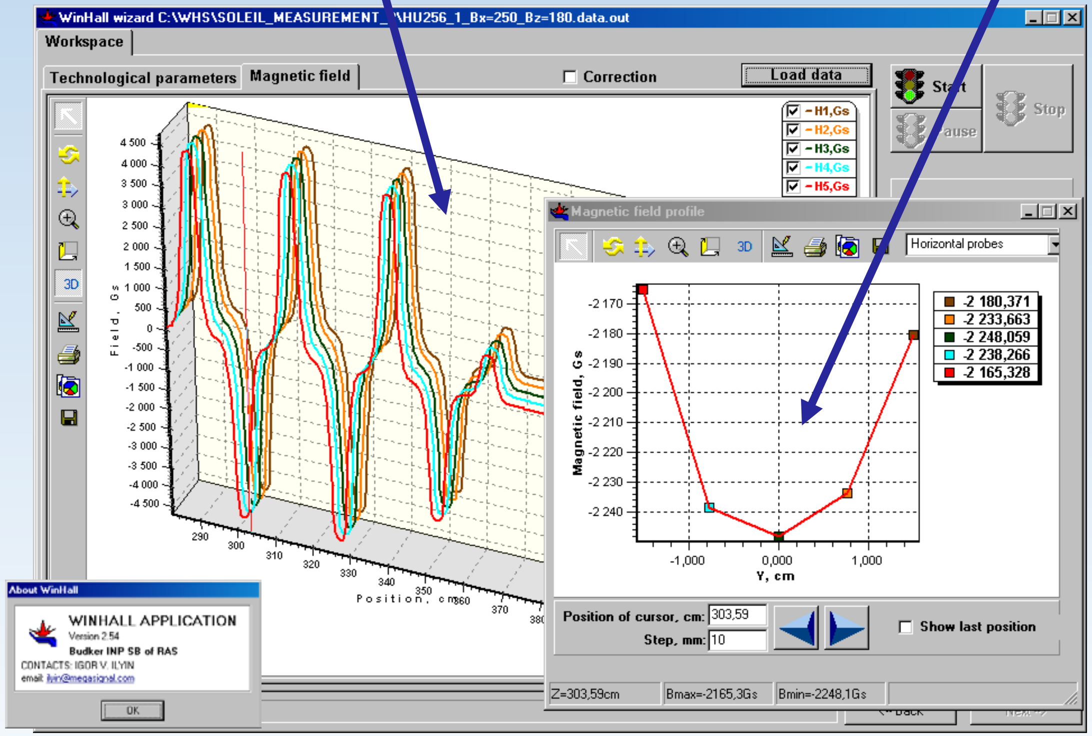
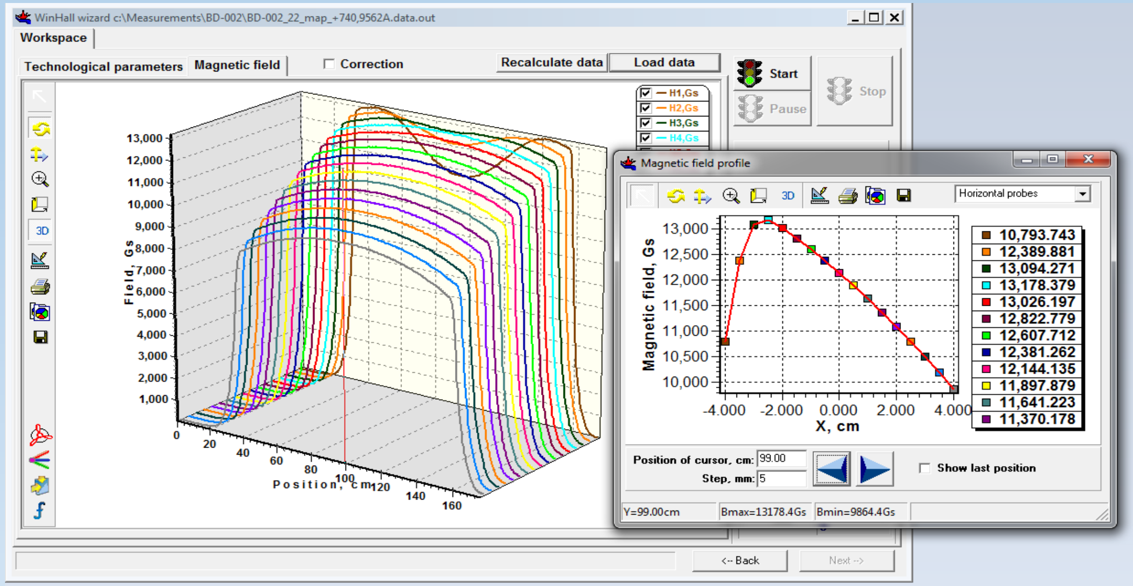
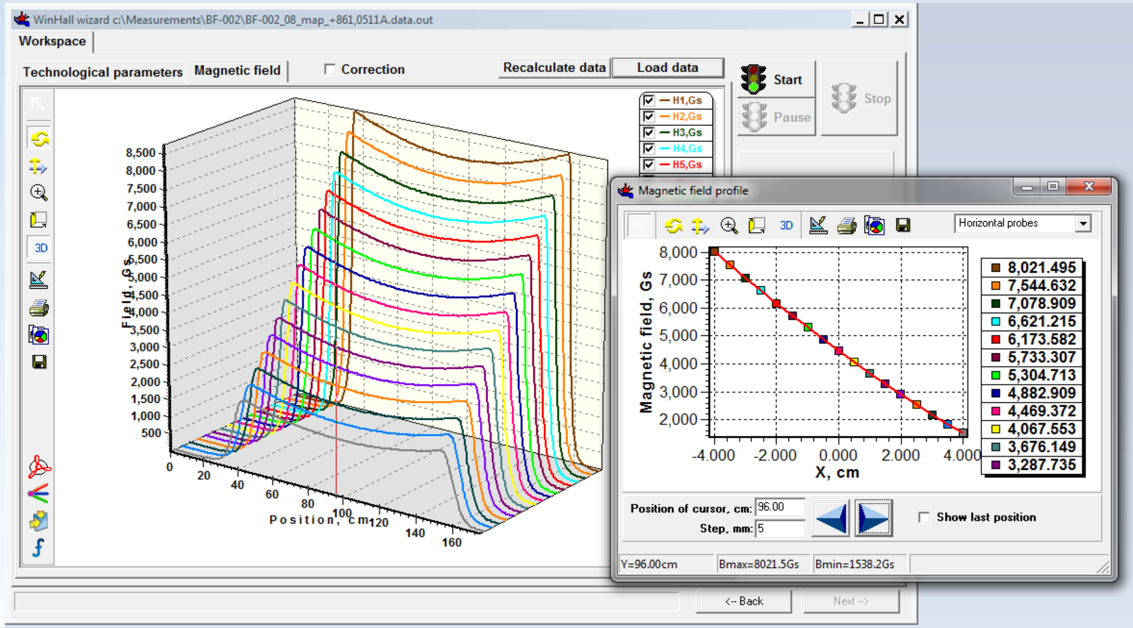
Software

Field map

The cross-section of the magnetic field in a given coordinate







Magnetic measurement setup based on pulsed NMR methods

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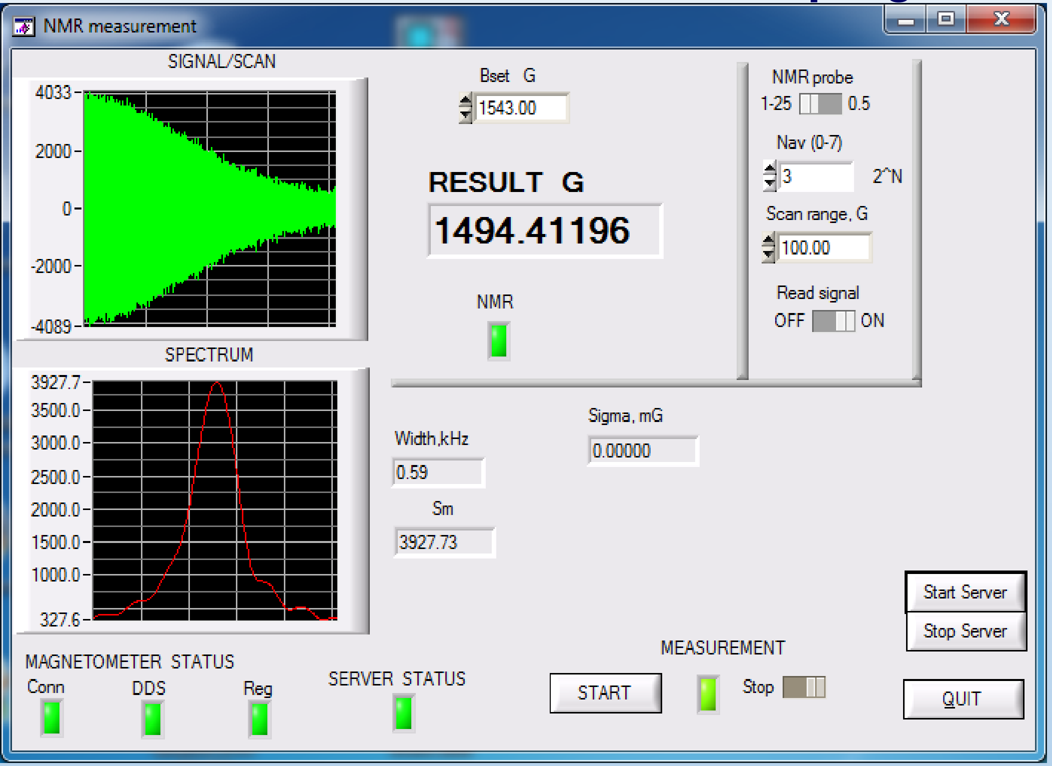
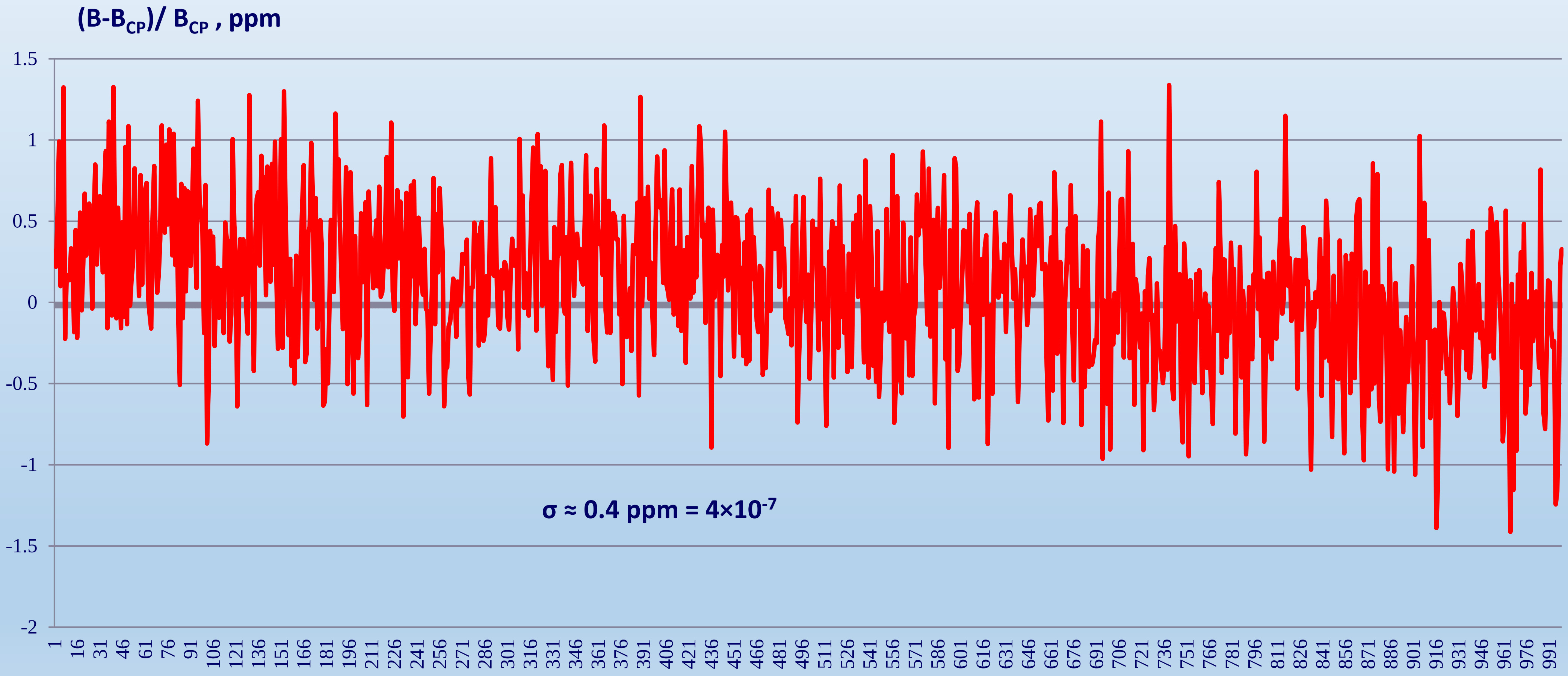
The window of the NMR program



The top picture shows the NMR signal after exposure of the RF excitation pulse.
In the lower picture shows the spectrum of the NMR signal.
The frequency of the NMR is obtained from this spectrum.
The magnetic field is calculated from the NMR frequency.

NMR sensor working substances	water, rubber, heavy water, Aluminum powder
Working cores of NMR sensors	Protons, deuterium, ^{27}AL
Range of measured magnetic fields: Sensors based on protons Sensors based on deuterium Sensors based on aluminum nuclei ^{27}AL	 0.03–3T 0.4–18T 1–10T
The possibility of measuring the field at the temperature of liquid helium	Sensors based on aluminum nuclei ^{27}AL
Number of channels	4
Minimum measurement time by one channel	~80 ms
Time of measurement by one channel at switching on “Frequency scanning mode”	2-4 s
The error in measuring the magnetic field by proton-based sensors at a measurement time of 80 ms: With a relative field gradient less than 10^{-4}/cm With a relative field gradient less than 4×10^{-4}/cm	 less then 2×10^{-6} less then 10^{-5}
The error in measuring the magnetic field by proton-based sensors at a measurement time of 1 s: With a relative field gradient less than 10^{-4}/cm With a relative field gradient less than 4×10^{-4}/cm	 less then 10^{-6} less then 3×10^{-6}
The error of measuring the magnetic field by sensors based on aluminum nuclei ^{27}AL at a measurement time of 1 sec: For the field 1 T For the field 5-10 T	 less then 10^{-4} less then 10^{-5}
Cable length from the NMR sensor to the Preamplifier	up to 7 м
Cable length from the Preamplifier to the main magnetometer	up to 150 м

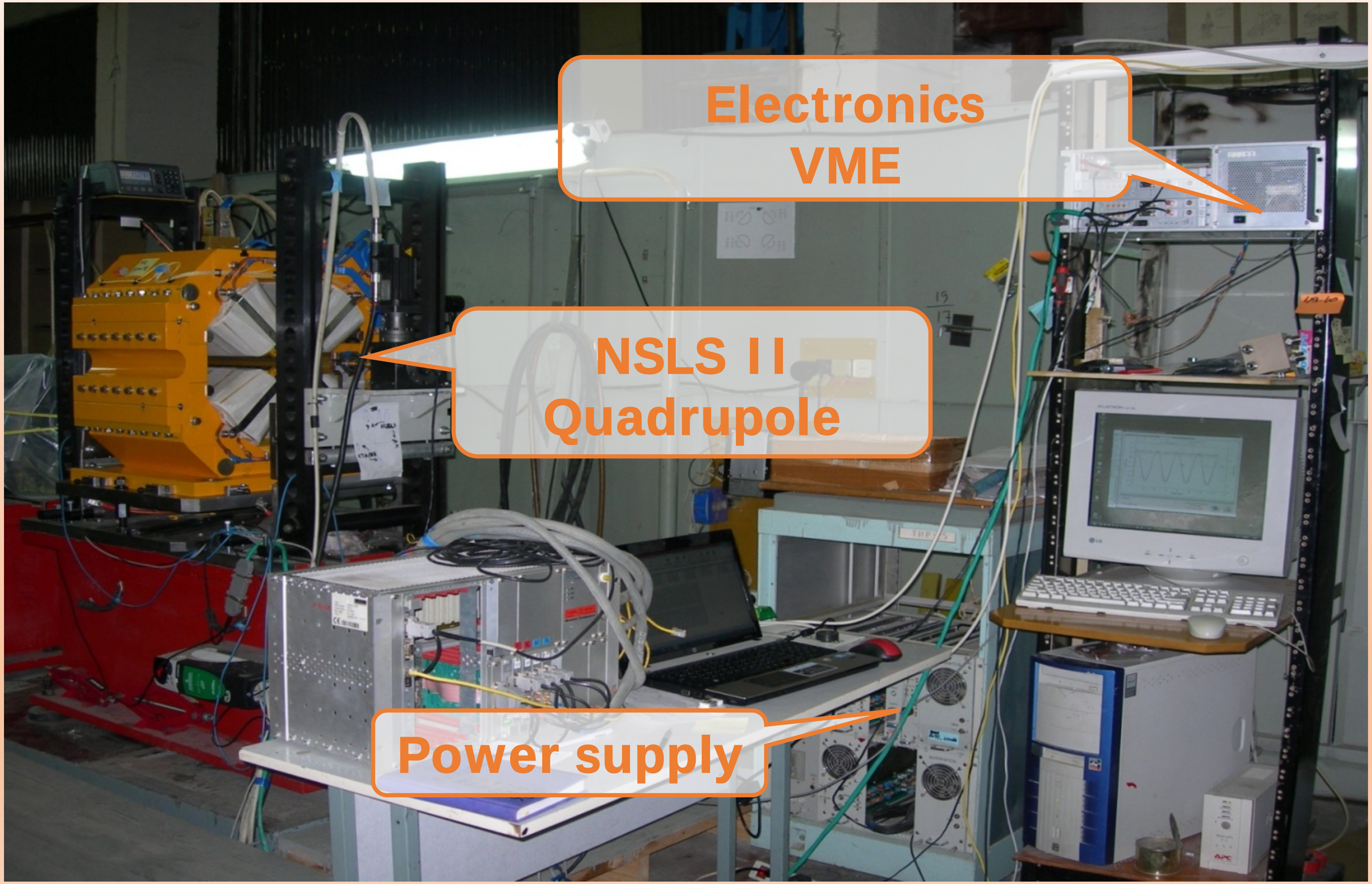
The results of measurements on a test permanent magnet with a field of 0.15 T and a gradient of about 0.2 Gauss/cm



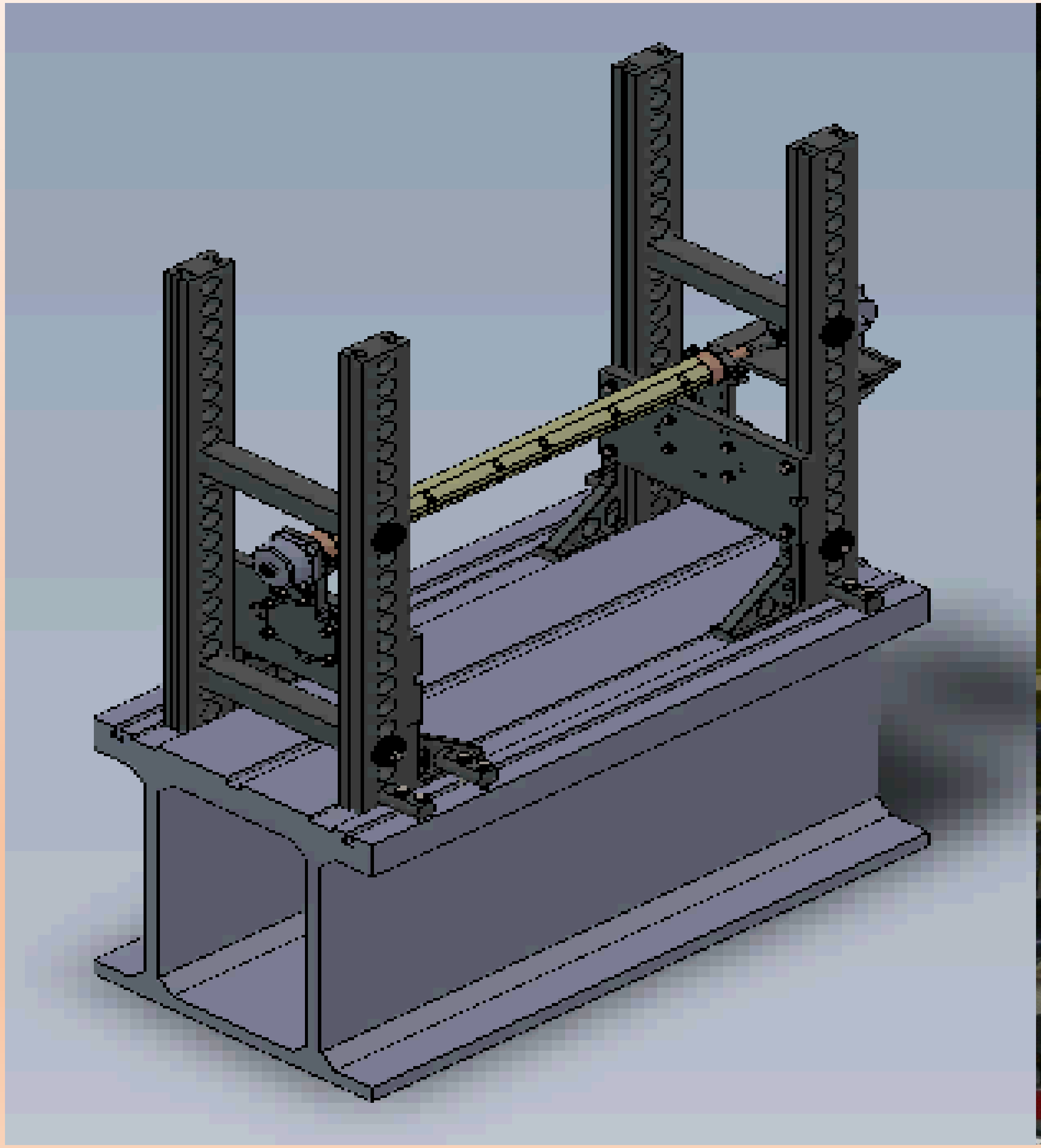
The normalized results of the measurements of the magnetic field with the time of one measurement is 100 MS for 5 minutes.

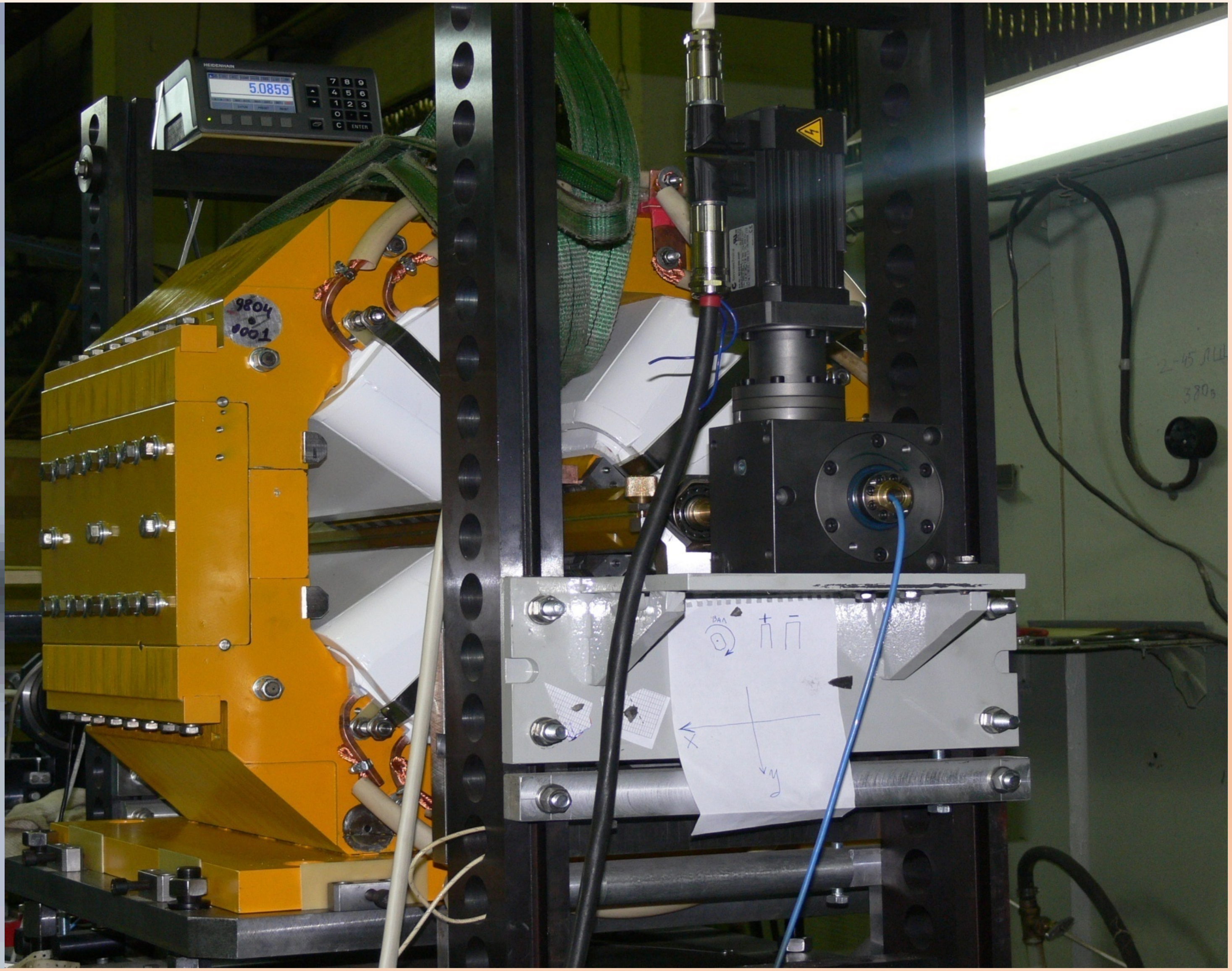
Rotated coil system

Rotating coils setup

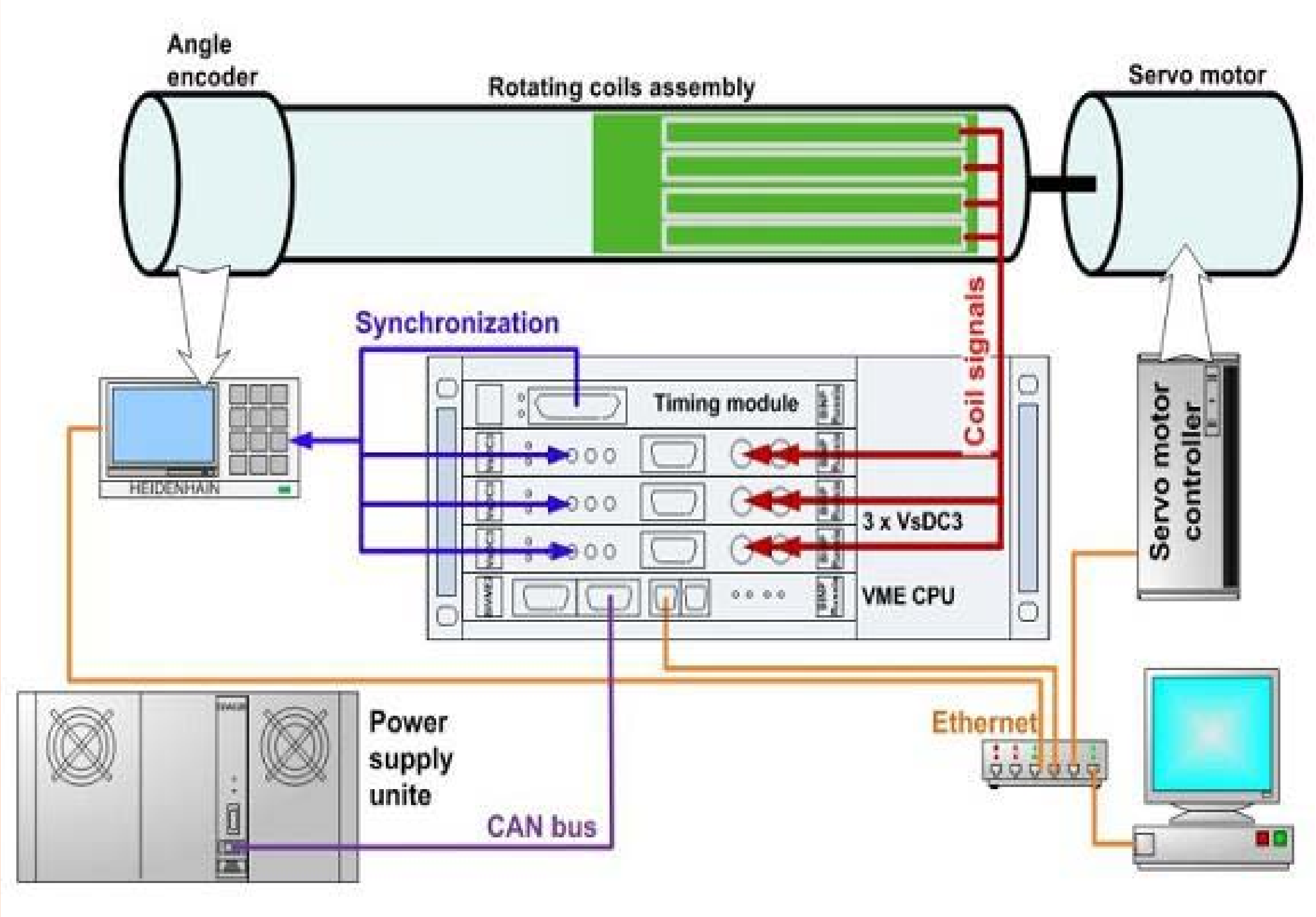


Rotating coils setup





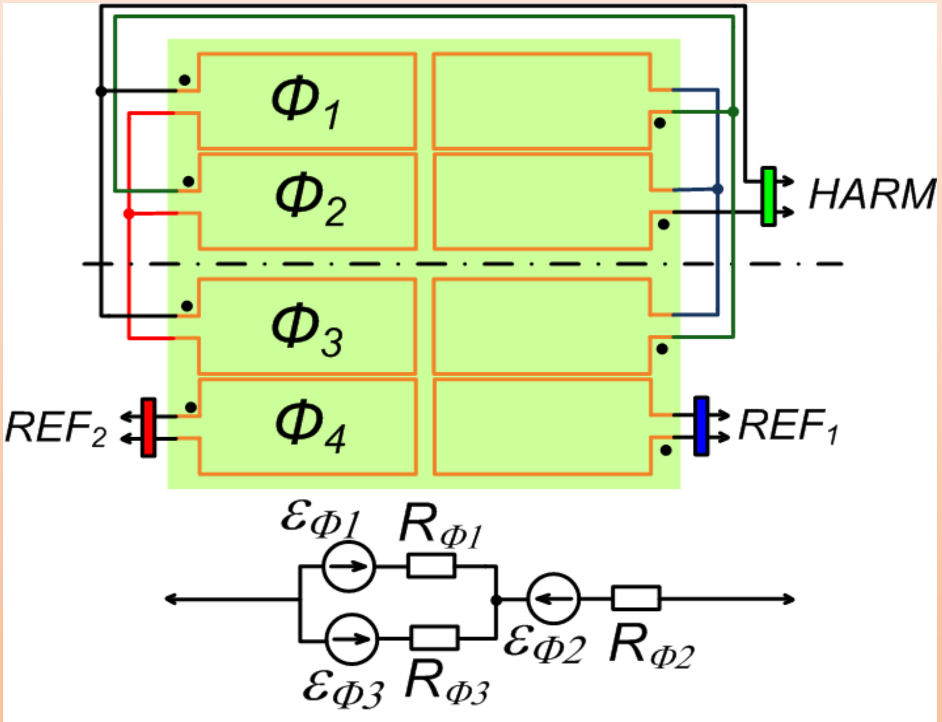
Rotating coils setup



Details in IMMW19: "The precise digital integration from microseconds to seconds: theory and implementation"

Coils Commutation

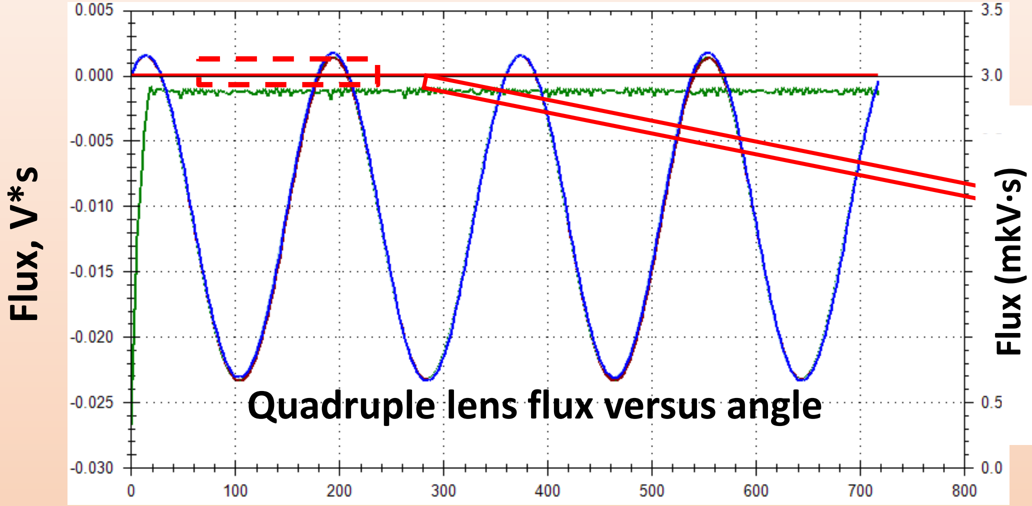
$$\Phi_{\Sigma}(\theta)=\frac{\Phi_1(\theta)+\Phi_3(\theta)}{2}-\Phi_2(\theta)$$

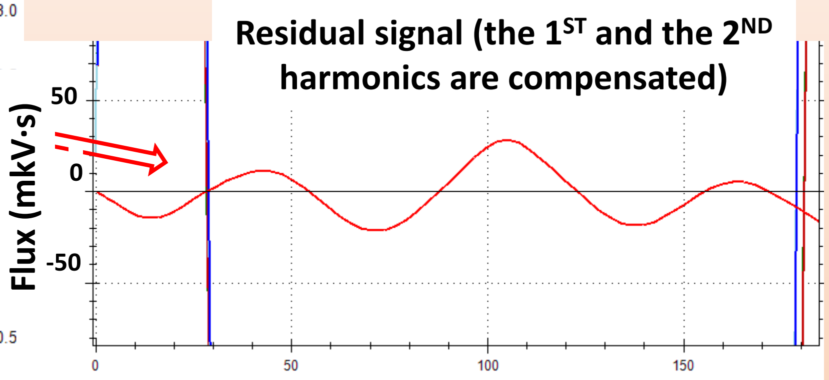


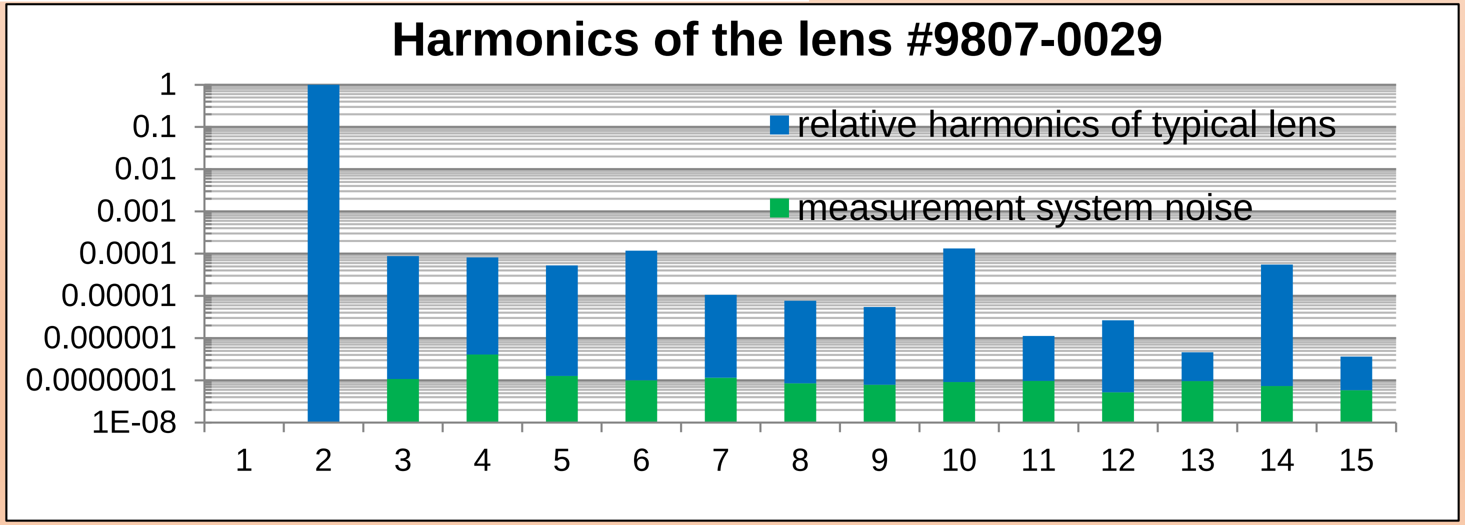
$$\varepsilon_{\Sigma}(t)=\frac{\varepsilon_1(t)+\varepsilon_3(t)}{2}-\varepsilon_2(t)$$

***Details in IMMW19:* “The precise digital integration from microseconds to seconds: theory and implementation”**

Measurements of the magnetic lens







***Details in IMMW19:* "The precise digital integration from microseconds to seconds: theory and implementation"**

Statistic of magnetic axis position for 30 measurements

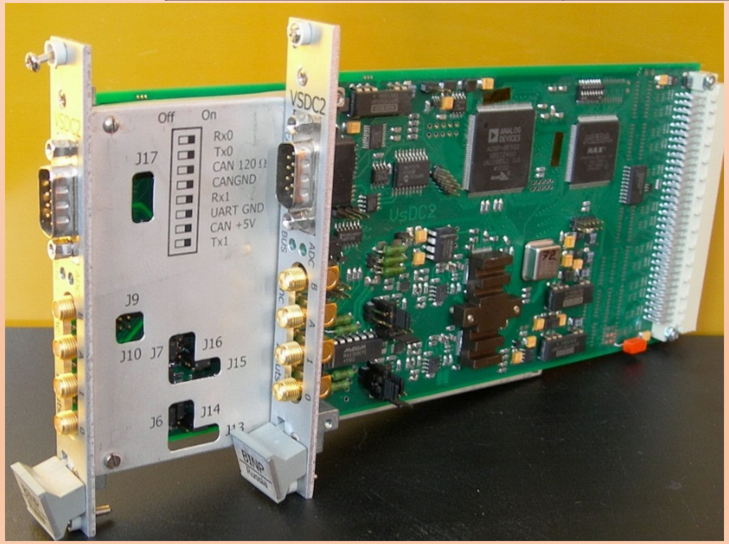
Standard Deviation:

D(x) = 6,26292E-01 mkm   D(y) = 7,13E-01 mkm

Digital integrators VsDC2 and VsDC3

VsDC – **V**olt-second to **D**igital **C**onverter

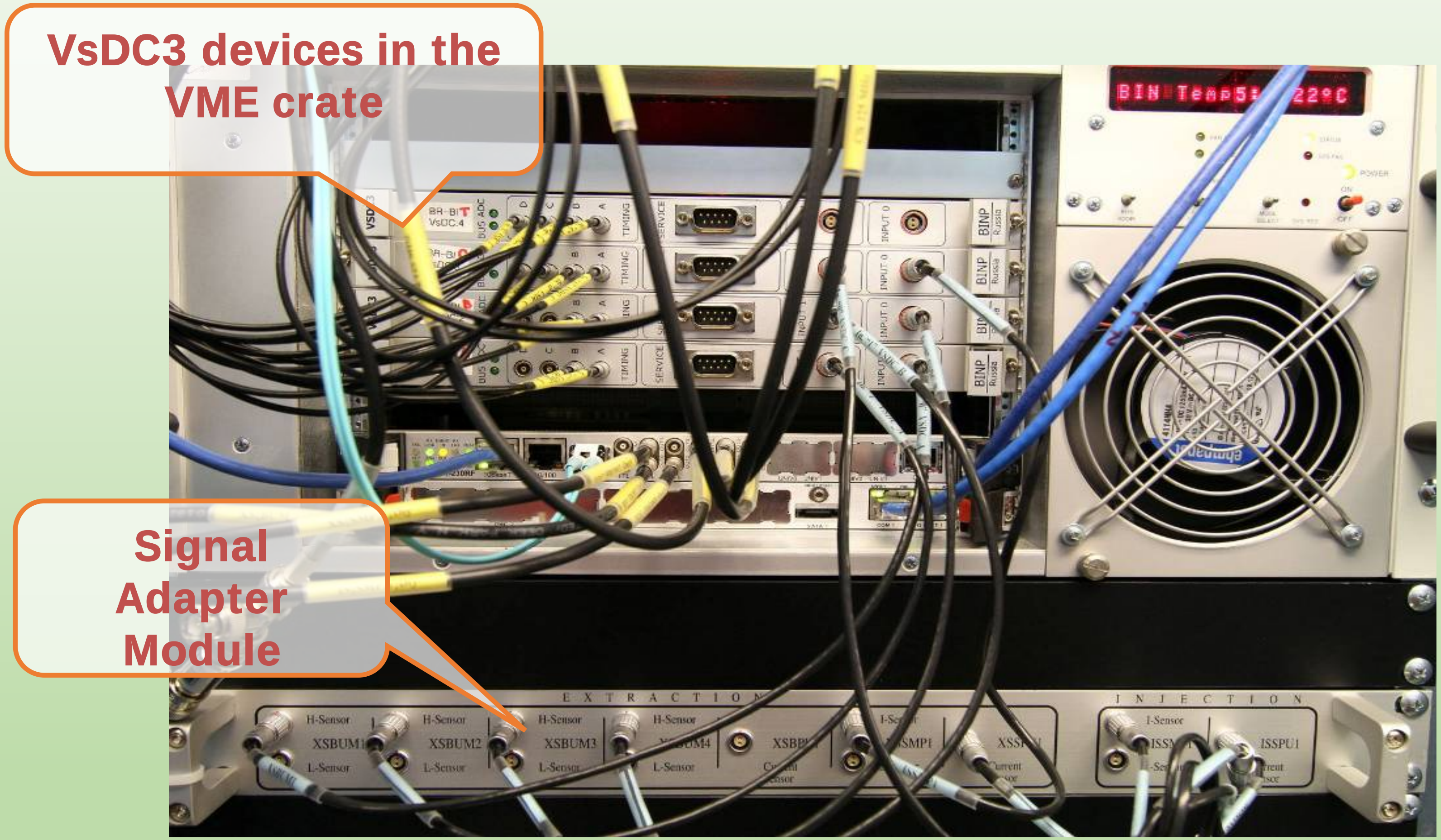
	VsDC2 (CAN version)	**VsDC3** (VME version)
# of channels	2	2
Input voltage ranges	±0.2V; ±0.5V; ±1V; ±2V; ±5V; ±10V	±0.2V; ±2V
ADC Sample rate	3.2 (1.6*) mks/sample	
ADC resolution	24 bit	
Footprint	3U 4HP Eurocard	6U 4HP Eurocard



Details in IMMW19: “The precise digital integration from microseconds to seconds: theory and implementation”

System for measuring pulsed magnetic fields

Pulsed field measurement system of the NSLS-II 3 Gev Booster Injection/Extraction channels



Measurement electronics in the NSLS-II Booster service area

Details in IMMW19: "The precise digital integration from microseconds to seconds: theory and implementation"

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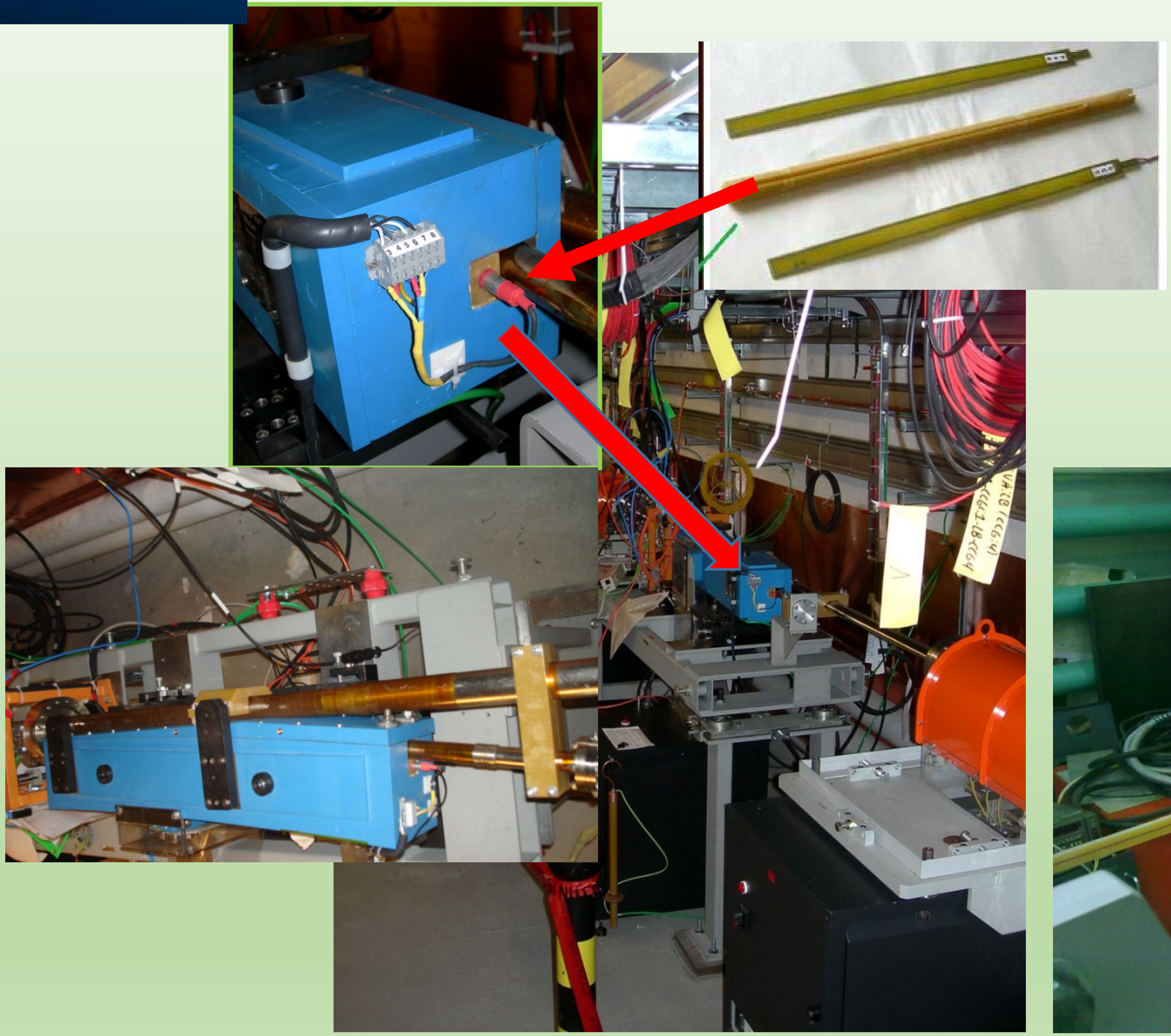
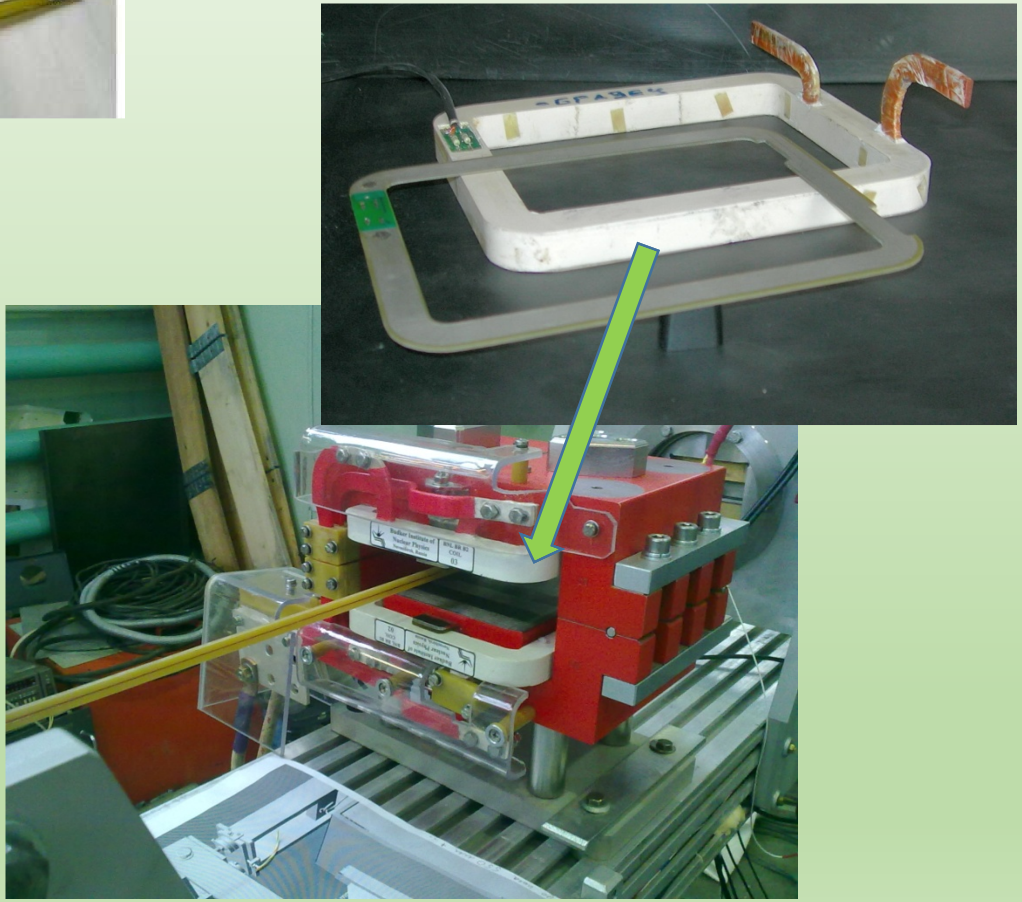
System for measuring pulsed magnetic fields





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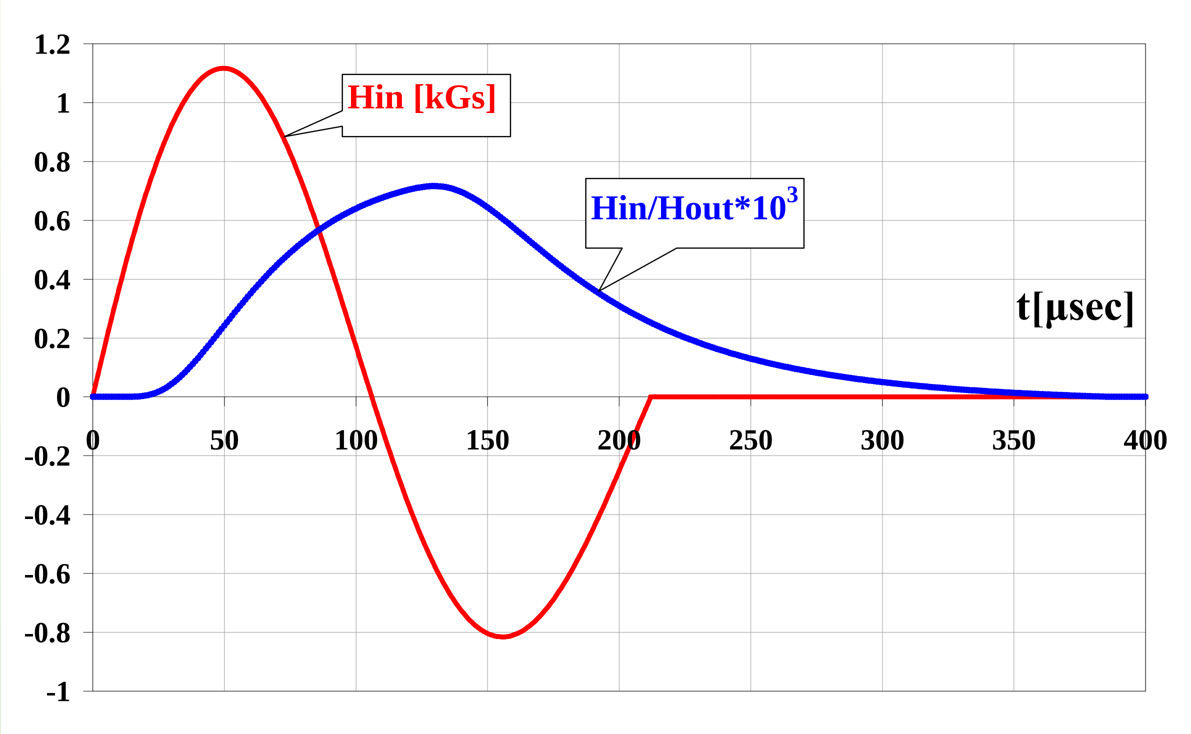
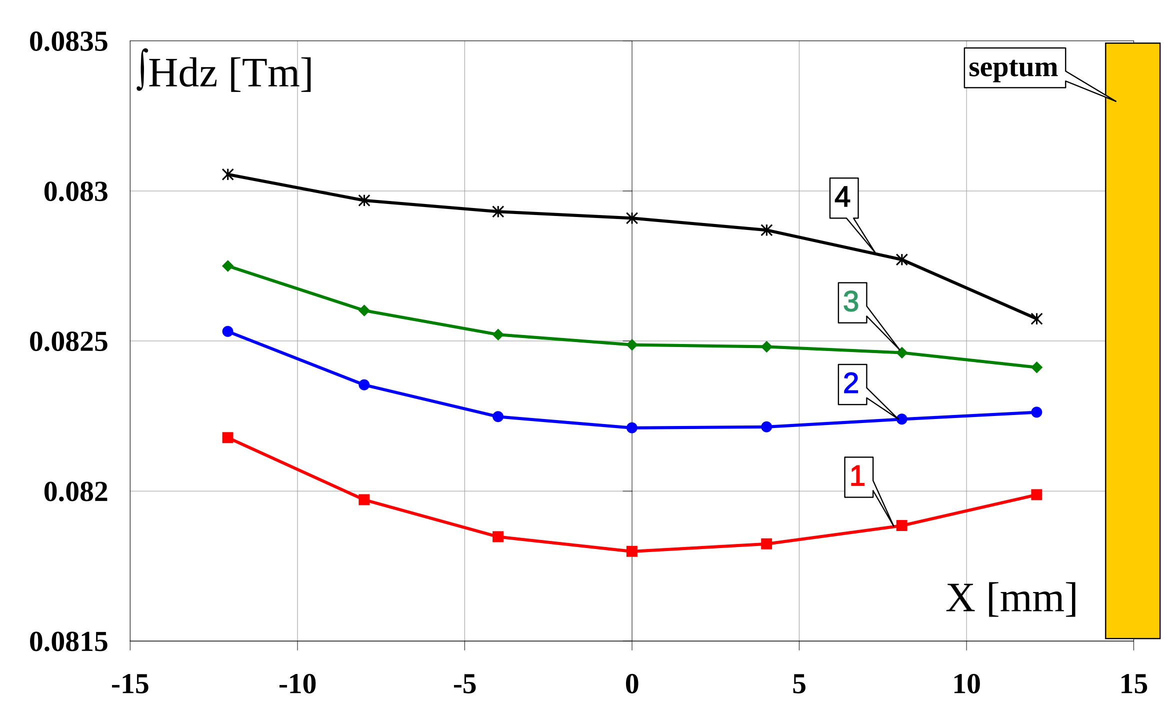
SEPTUM MAGNET



Magnetic field in injection magnet and stray field in vacuum chamber of the booster subject to time.

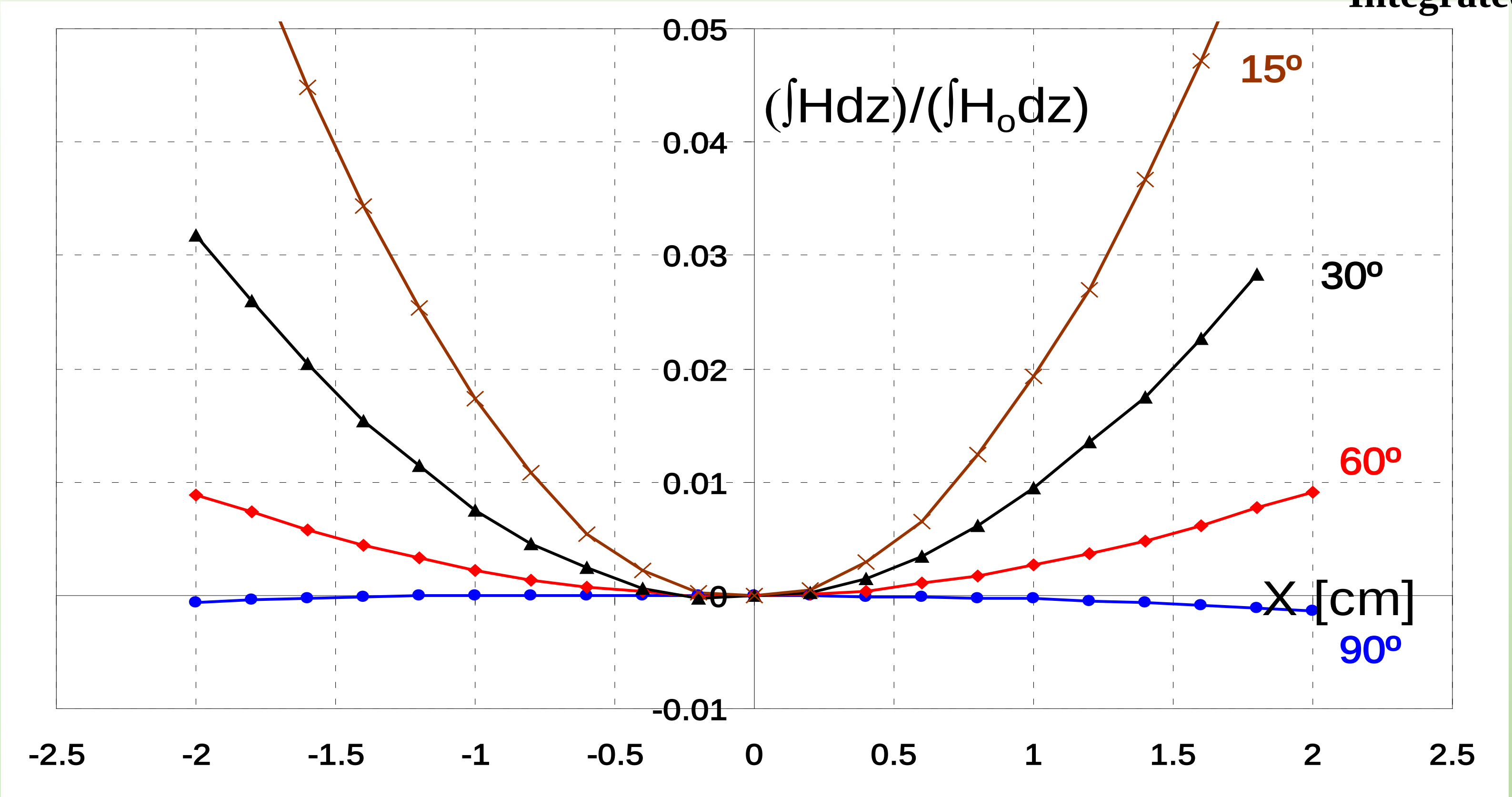


Distribution of integral of a field on radius in various phases of a feeding impulse.

1 - t=52.5 µs, 2- t = 53.5 µs, 3- t = 54.5 µs, 4- t = 56.5 µs.

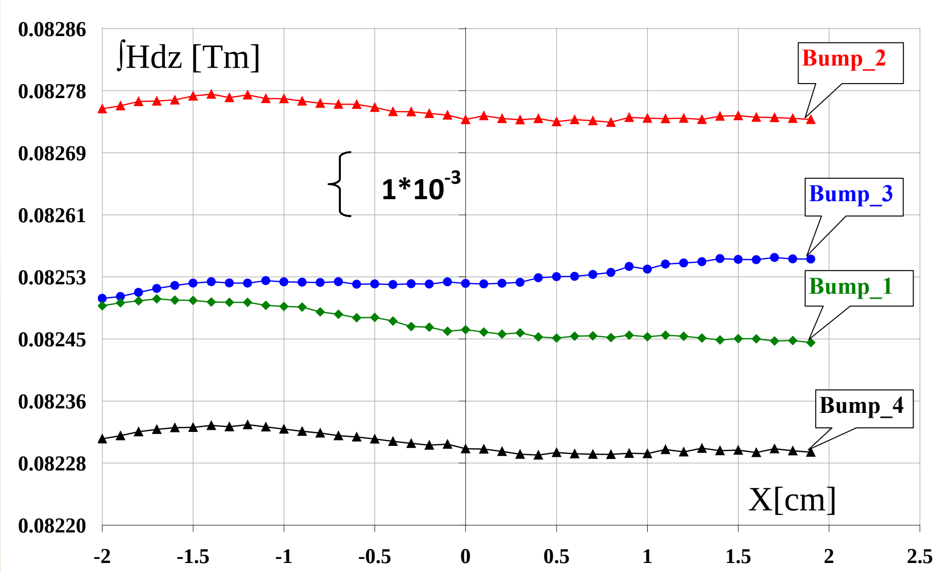
PULSED MAGNETS FOR INJECTION AND EXTRACTION SECTIONS OF NSLS-II 3 GEV BOOSTER A.Zhuravlev, Proceedings of IPAC2013, THPME033

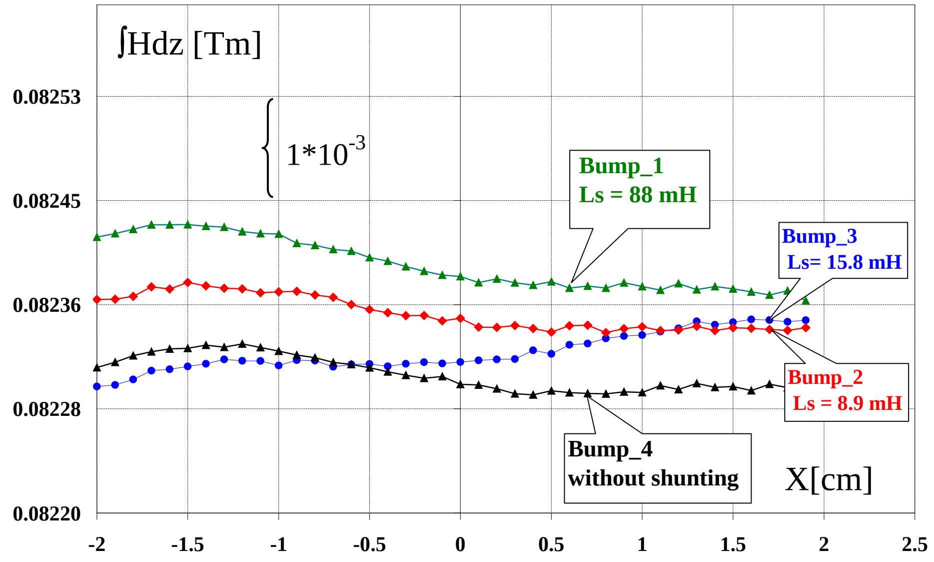
System for measuring pulsed magnetic fields



Inhomogeneity of the field integral in the
bump magnet normalized on field integral in the center
for various phases of a current pulse.

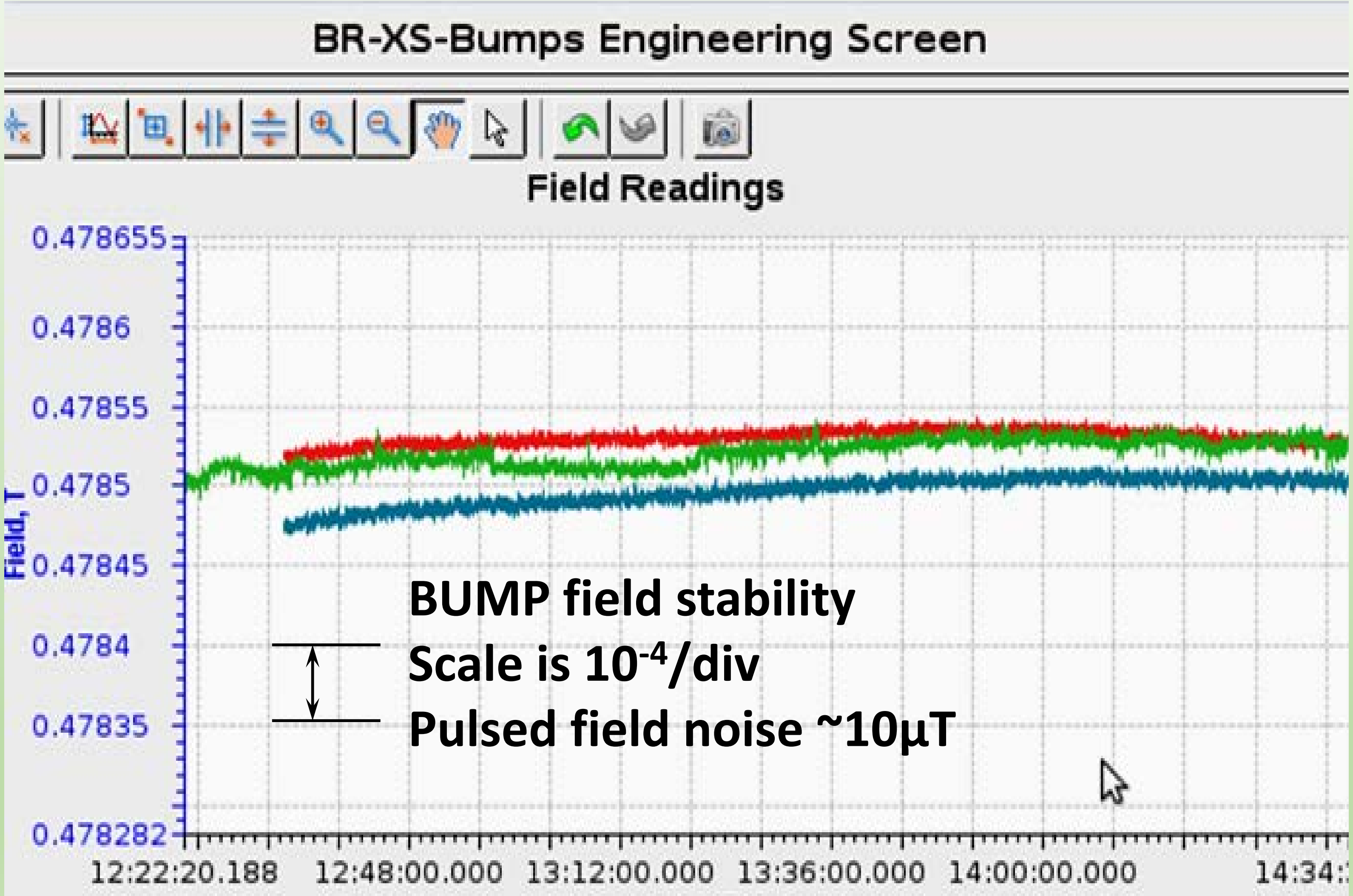
Integrated value of a field bump-1-4 with vacuum chamber





Integrated value of a bump - 1-4 fields with vacuum chamber and with shunting.

Pulsed field measurement system of the NSLS-II 3 Gev Booster Injection/Extraction channels

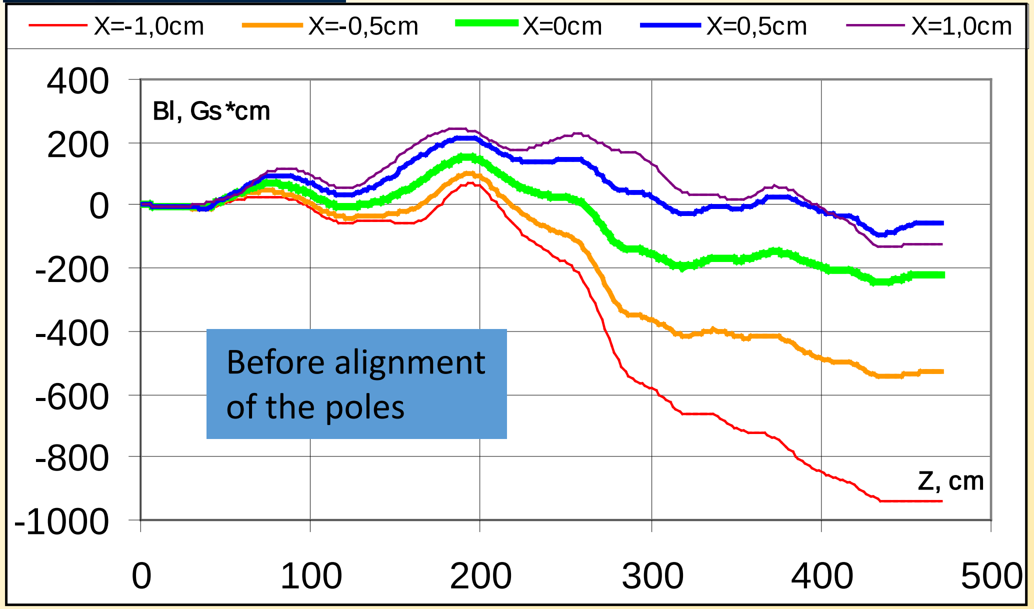


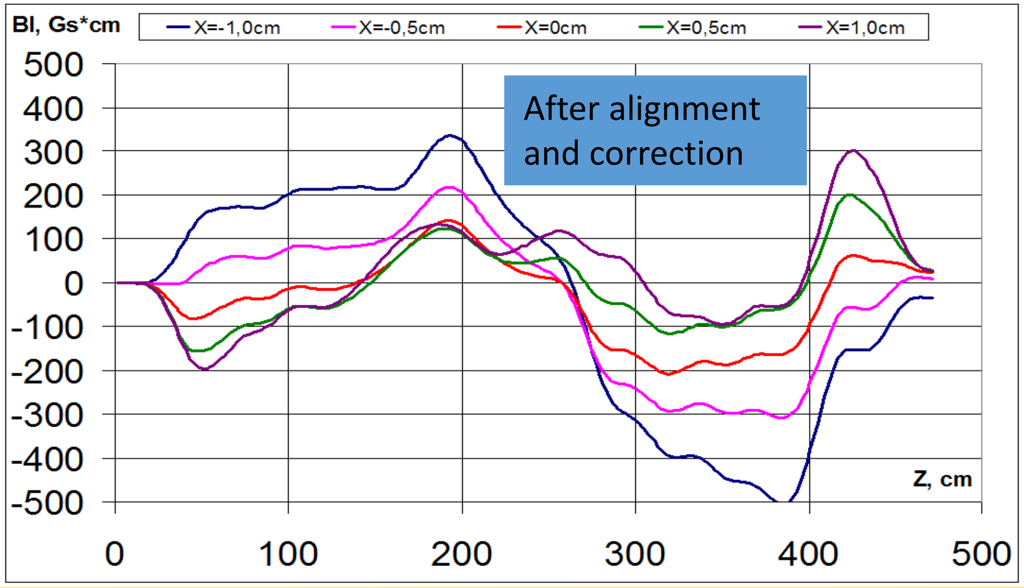
- Stability meets the requirements

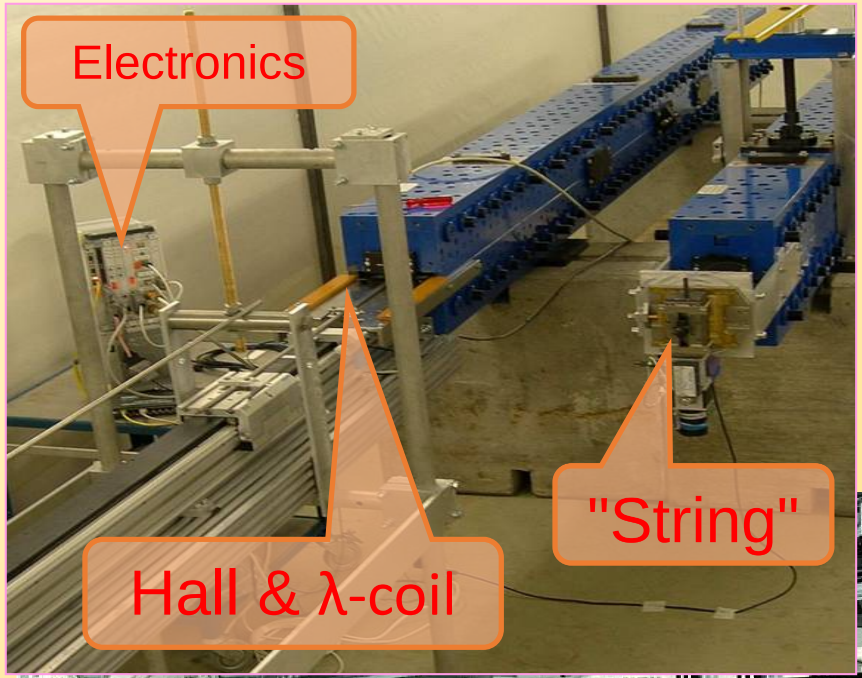
Stretched wire and λ-coil

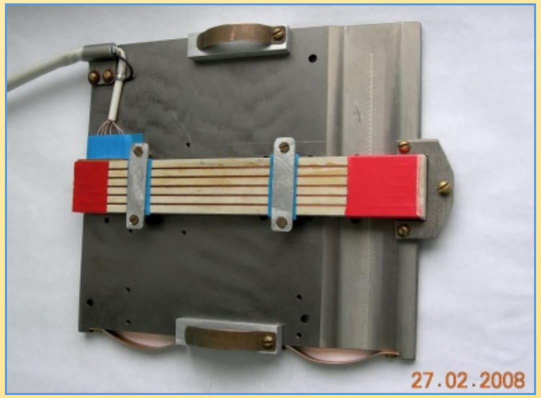
IMMW20
International Magnetic Measurement Workshop
4th - 9th June 2017, Diamond Light Source

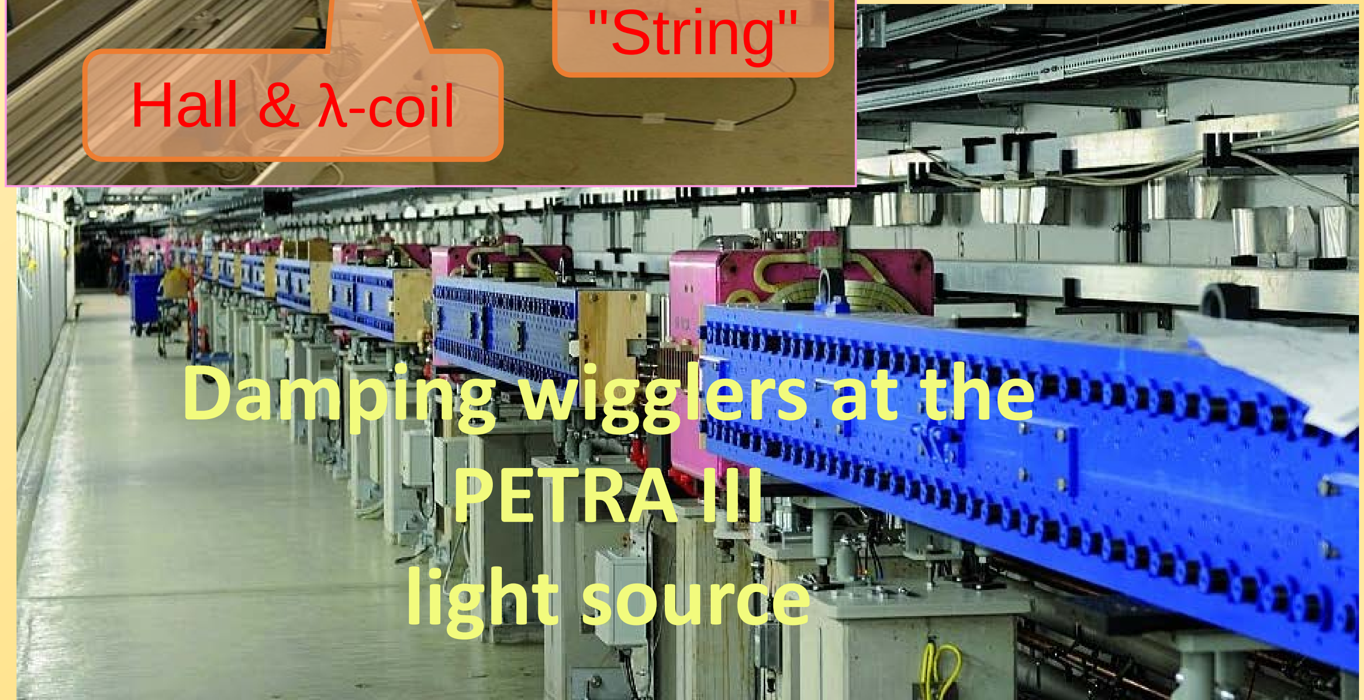
The behavior of the 1st horizontal field integral along the wiggler at 5 points on the aperture (X), the measured λ-coil



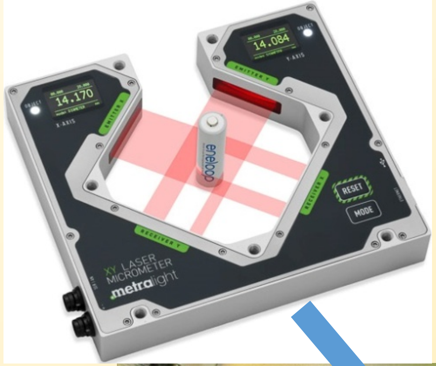




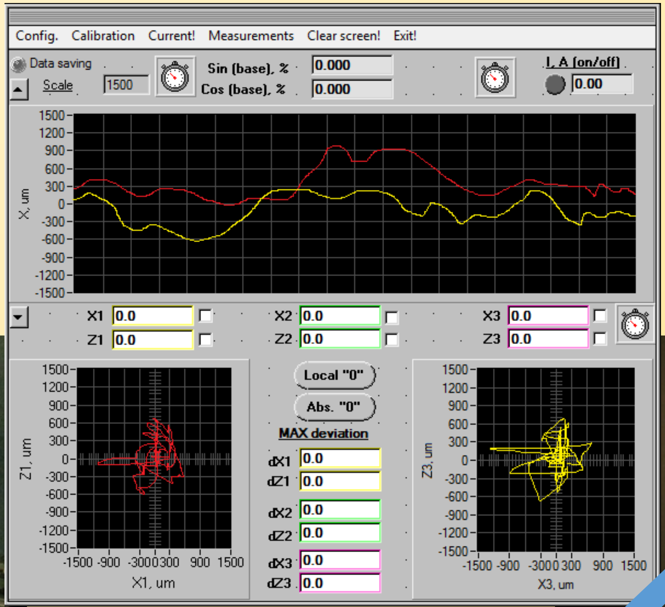


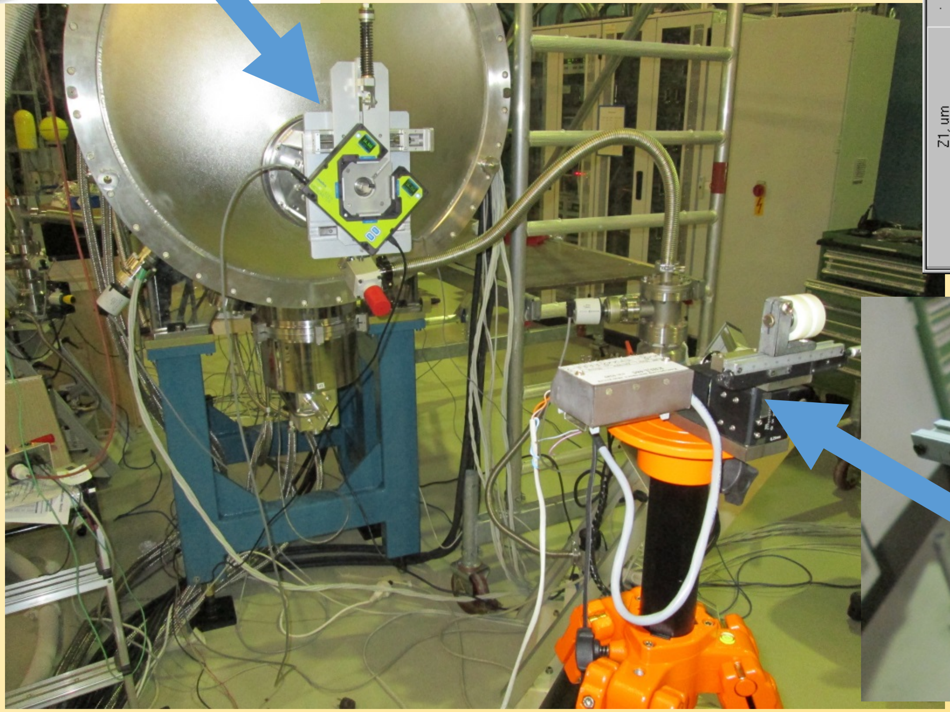


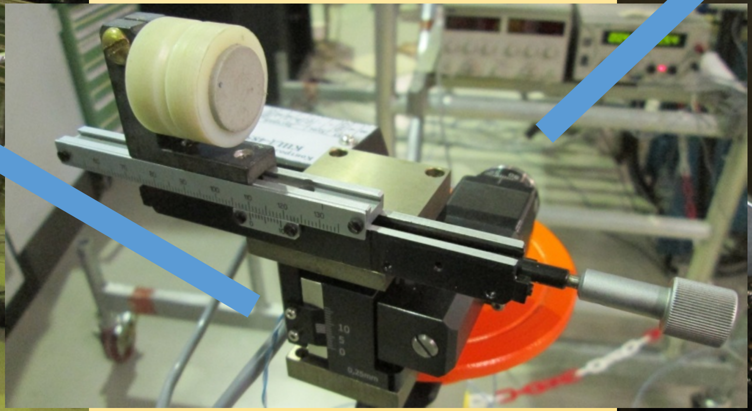
Stretched wire for superconductive Wigglers

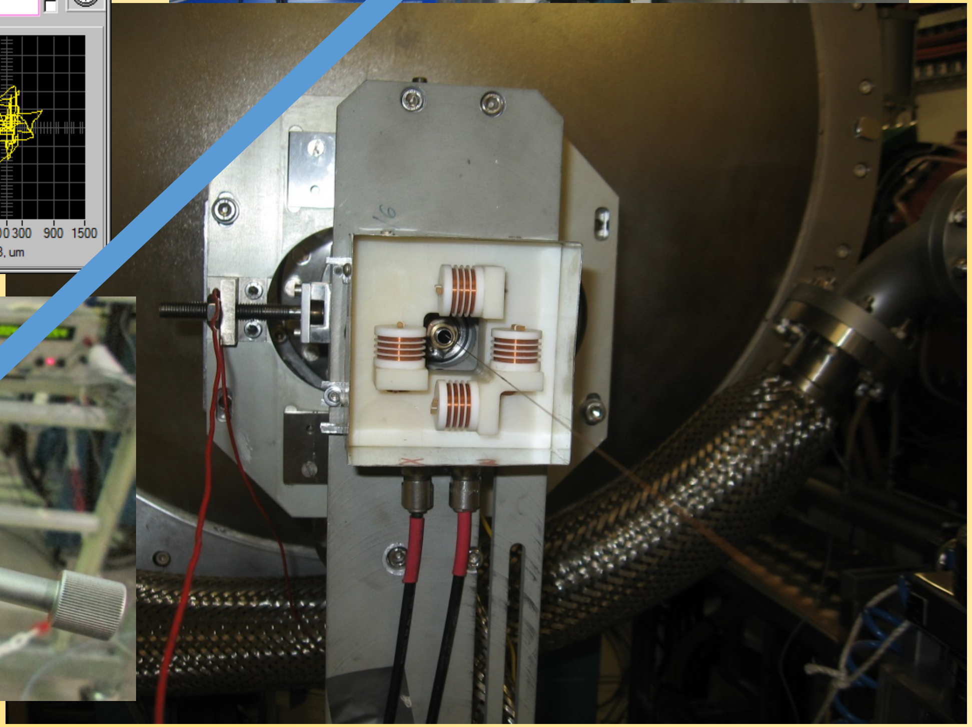


- 2 “microXY” 2-axes laser micrometers
- 0.5 um resolution
- 1250 measurements/second, all sensors (2 x and 2 z) work simultaneously
- USB connection









Conclusion

- There are widely used all the classic methods of measurement of magnetic field In the BINP
- Electronics developed in BINP allows to conduct experiments at a high international level
- For all measurements we use power supplies designed and assembled by BINP
- For precision transfer of the magnetic axis BINP uses coordinate measuring machine such as a Laser Tracker, ZEISS Contura G2, etc.

IMMW20 International Magnetic Measurement Workshop 4th – 9th June 2017, Diamond Light Source

Acknowledgement

In this presentation author used articles of the following people:

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A.A. Starostenko, A.N. Zhuravlev, V.A. Kiselev,

A.V. Zorin

Thank you for attention
Welcome to Siberia

Additional information

Product groups

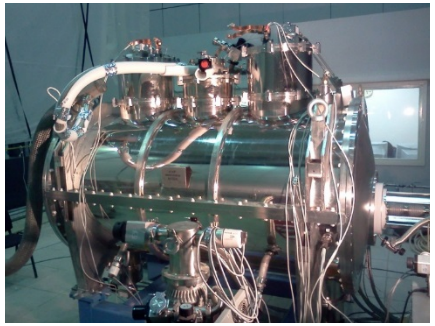
Magnets

Undulators

PS and electronics

Compact neutron source

Industrial
e- accelerators



SC wigglers

Cryogenic
equipment

MW ion injectors

High vacuum systems

BNCT

X-ray scanners

e- cooler

RF systems

Turn-key accelerator
facilities

Products
Magnets

Dipoles (360 pcs.) and quadrupoles (180 pcs.) for LHC (CERN, 1996-2001)

Quadrupoles for Rutherford Lab. 6t. (10 pcs., Great Britain, 2010)

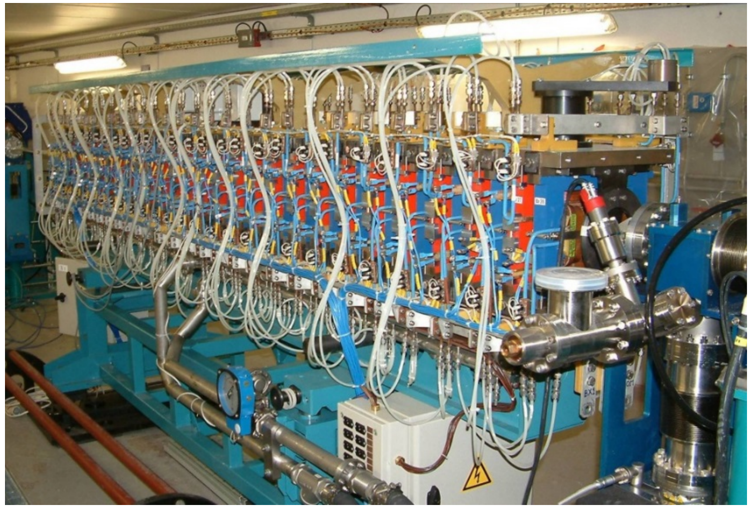
Radiation resistant dipole 90t. for FAIR (Germany, 2012)

Quadrupoles and sextupoles for SR ALBA (250 pcs., France, 2008)

Dipoles for PETRA III (13 pcs., Germany, 2013)

Quadrupoles SR NSLS II (225 pcs., USA, 2013)

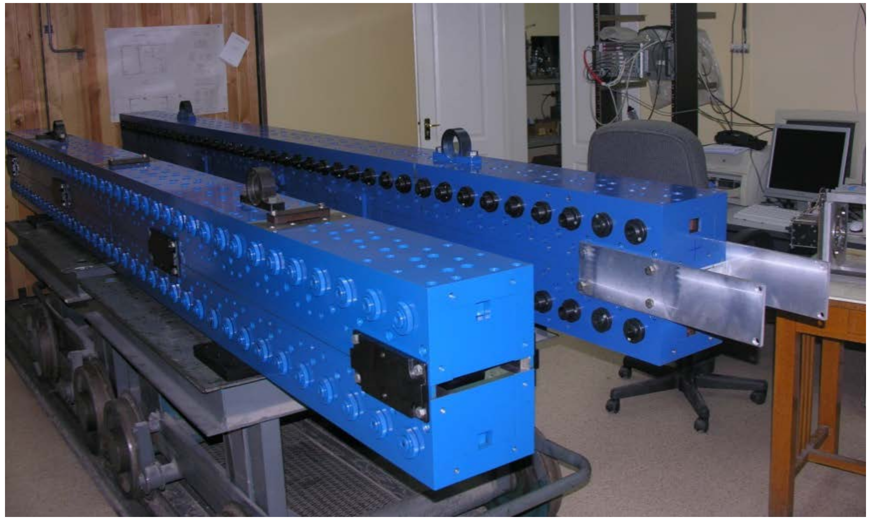
Products Undulators & Wigglers



Undulator for SOLEIL (3 pcs., France, 2009)

Undulator (prototype) for XFEL (Germany, 2014)

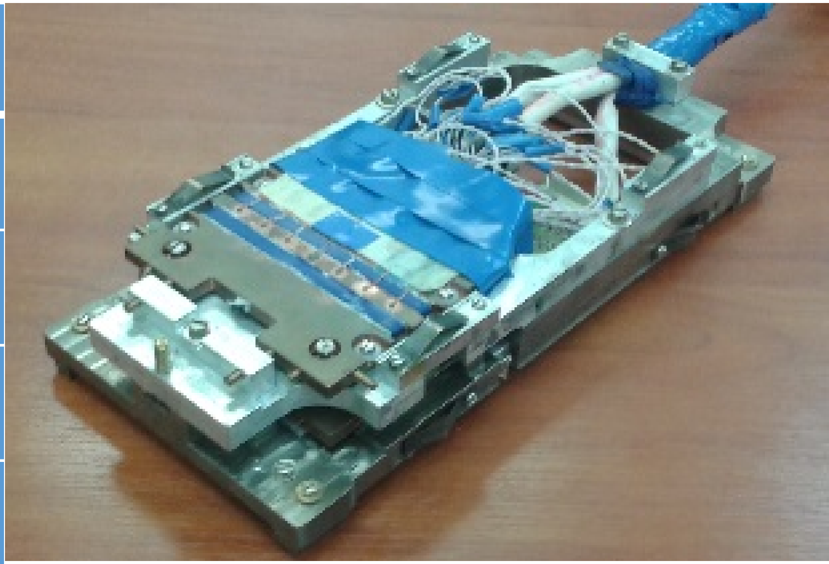
Undulator for SLS PSI (2 pcs., Швейцария, 2004)



Dumping wigglers for PETRA III (24 pcs., Germany, 2010)

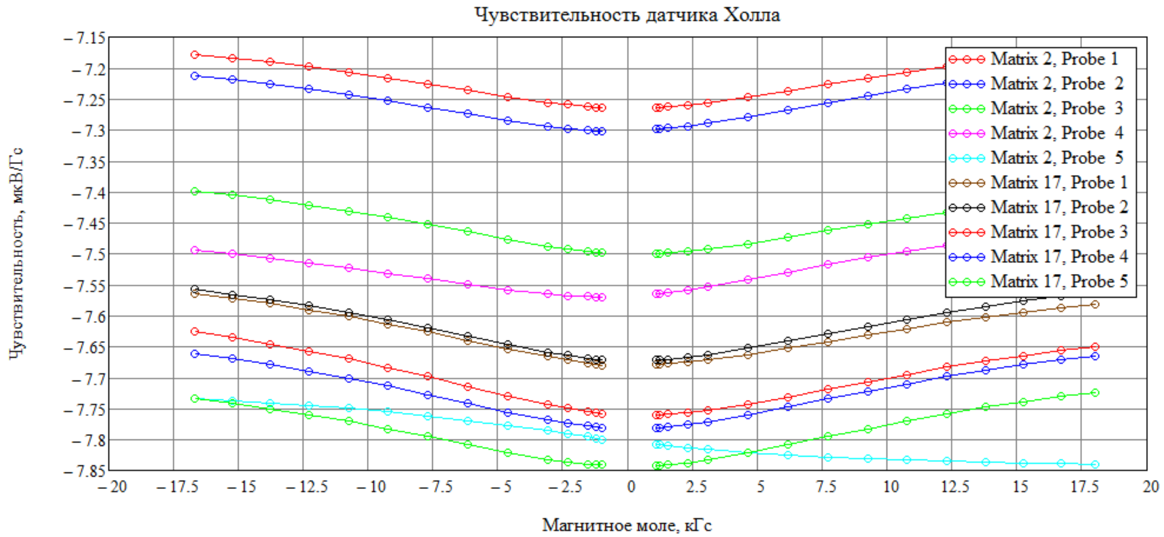
Typical accuracy to the carriage and Hall sensors

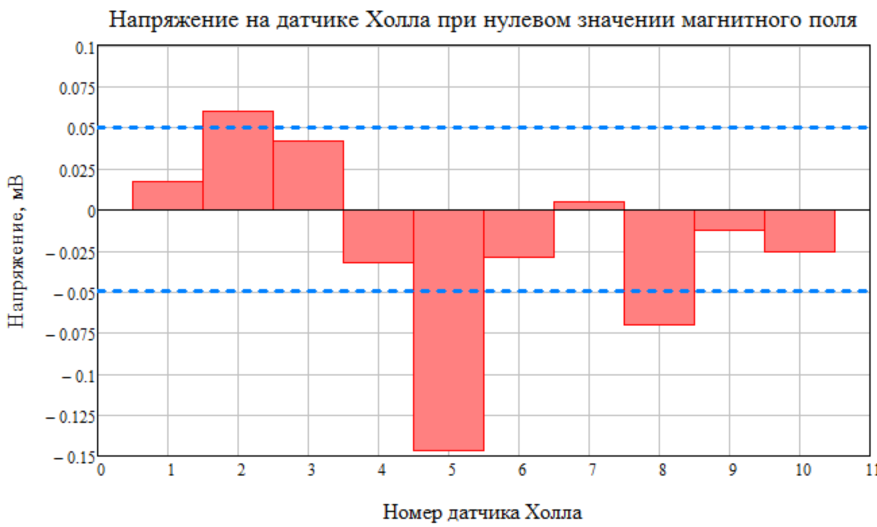
Option	Tolerance
The positioning accuracy of the Hall sensors (relative), X, Y, Z	±20 um
The positioning accuracy of the carriage of Hall sensors (absolute), X, Y	±50 (±100) um
The positioning accuracy of the carriage of Hall sensors (absolute) Z	±0.5 mm
The deviation of the axis of the sensor relative to the median plane	±20 mrad
Not parallel to the plane of the carriage and the median plane of the magnet	±0.5 (±1.0) mrad
Error field measurement by Hall sensor (sensor calibration)	±0.5 Гс
Error field measurement by Hall sensor (zero sensors)	±0.5 Гс

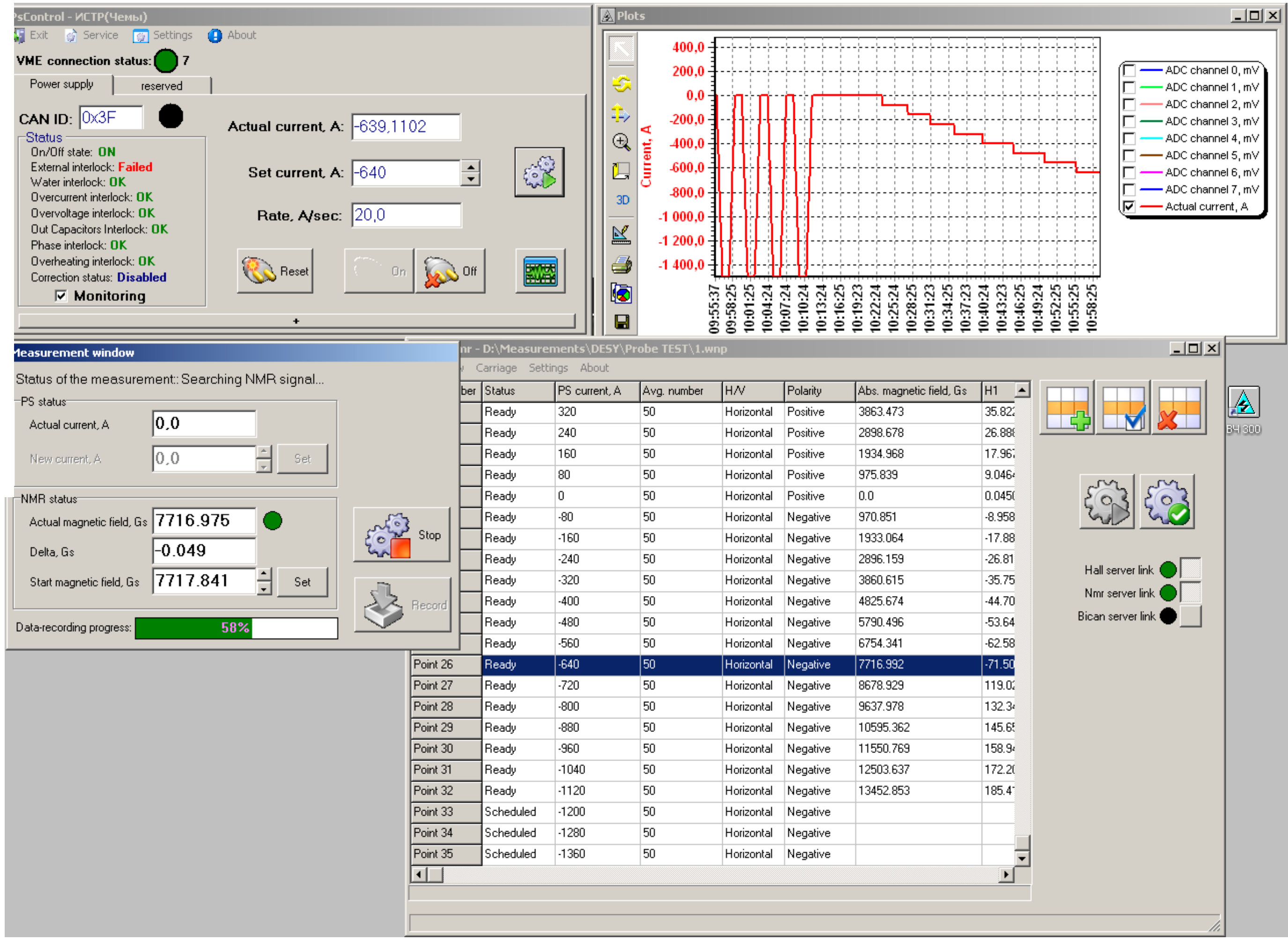


Параметр	dA/A
ΔB/B (ΔL/L)	$4*10^{-4}$
ΔG/G	$8*10^{-4}$
ΔS/S	$1.4*10^{-3}$

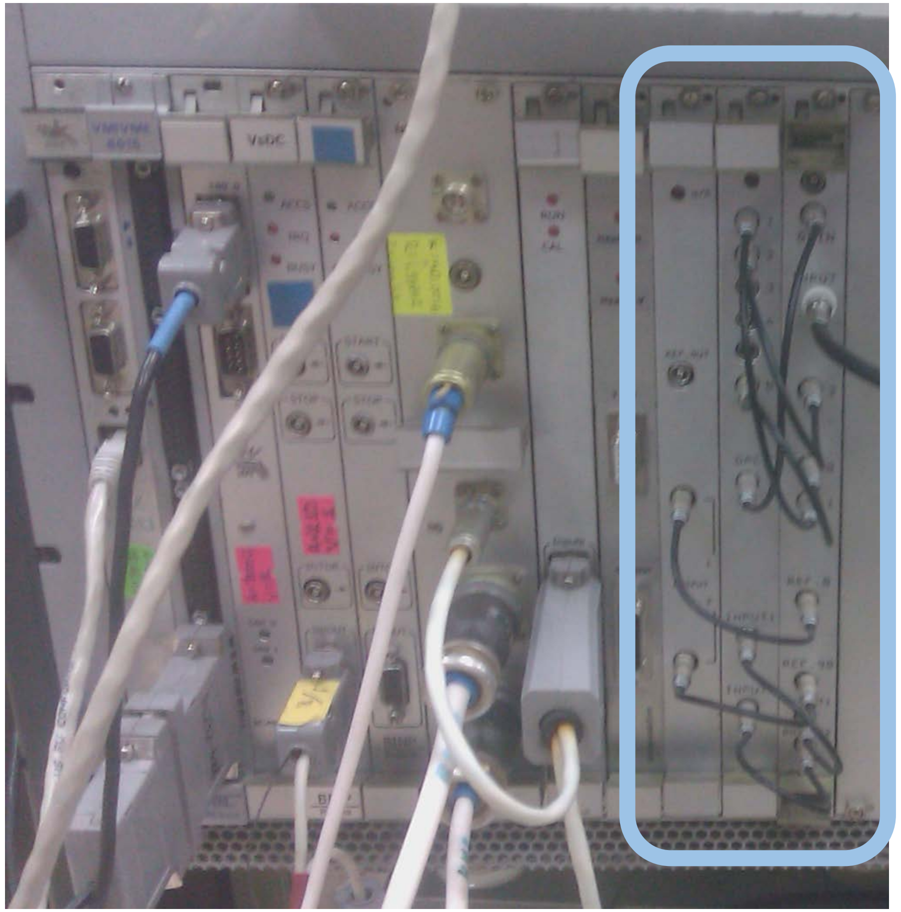
Example of calibration of Hall sensors using a NMR sensor

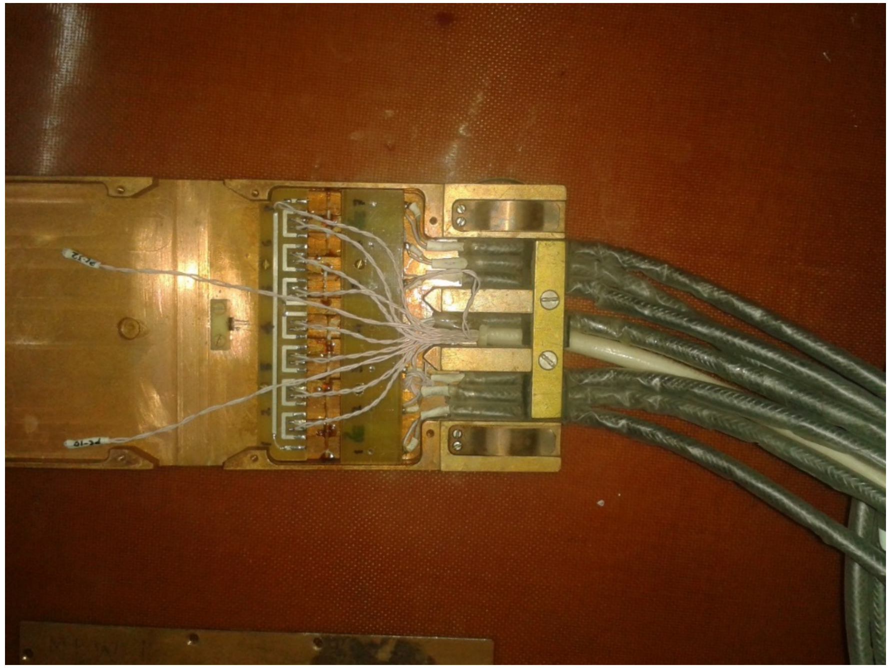




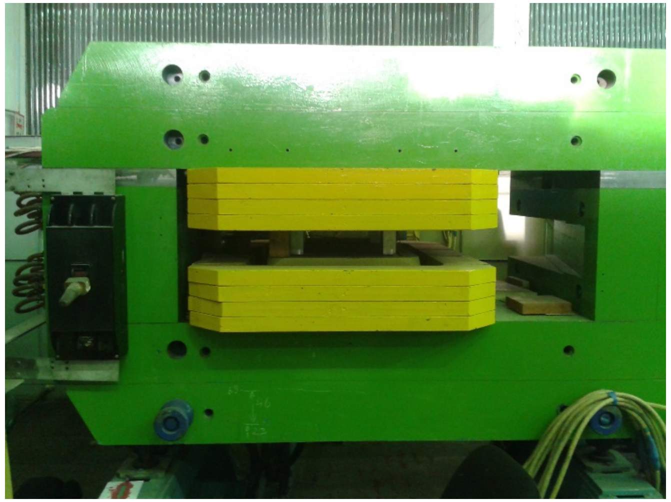


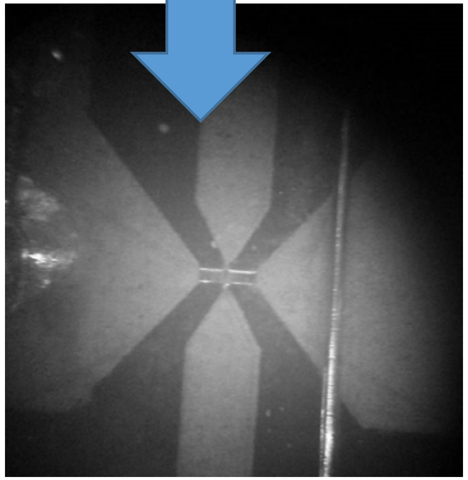
The NMR sensors and electronics

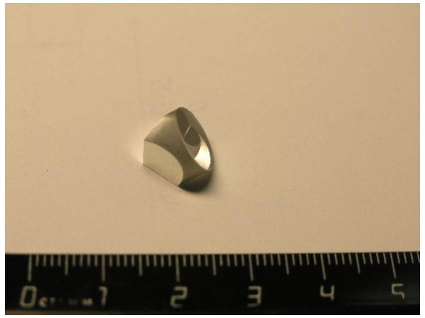




Additional equipment

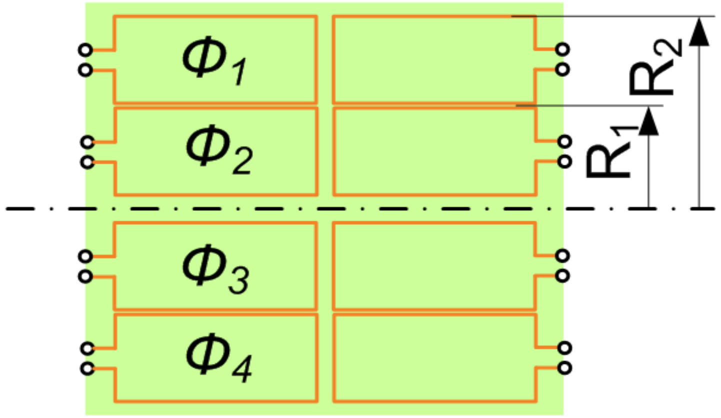






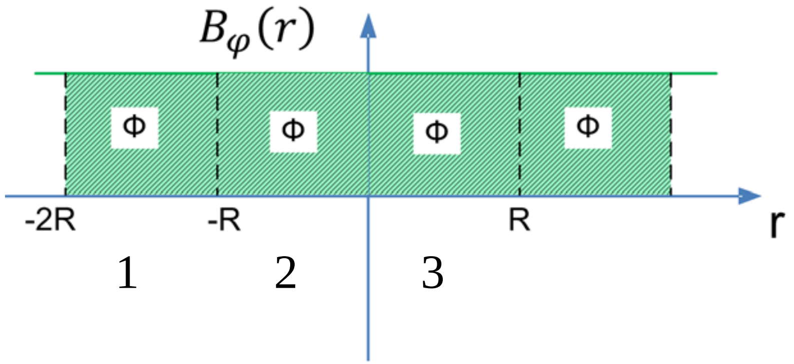
Coils Commutation

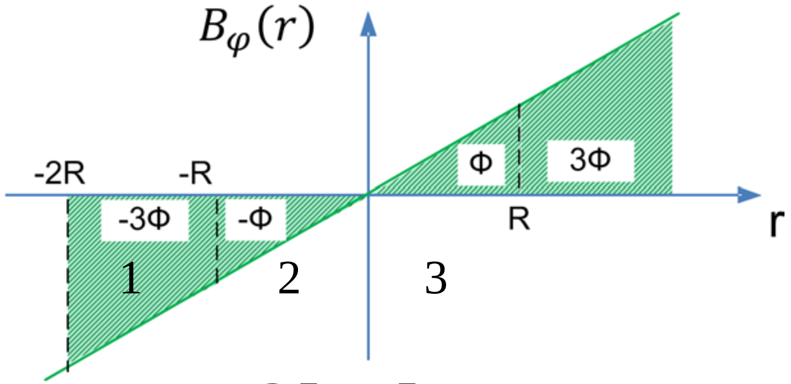
BINP, Russia



$$\Phi_\Sigma(\theta) = \frac{\Phi_1(\theta) + \Phi_3(\theta)}{2} - \Phi_2(\theta)$$

If R2 = 2*R1, therefor the dipole and quadruple components doesn't influence to the flux:

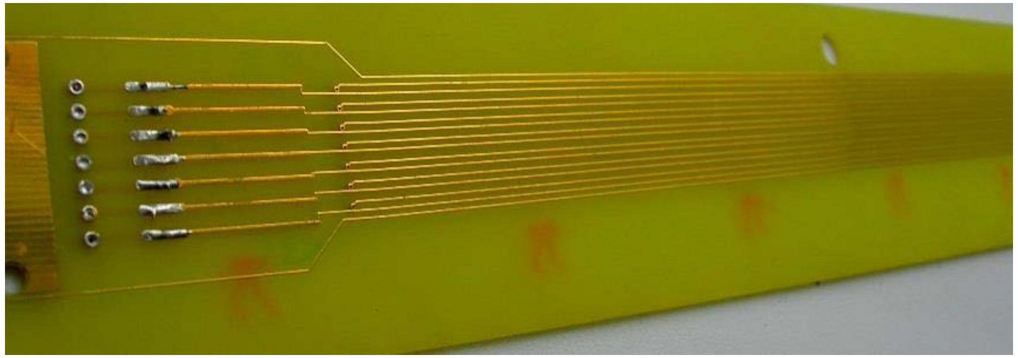


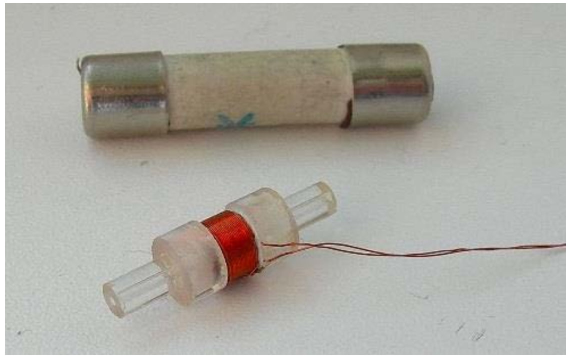


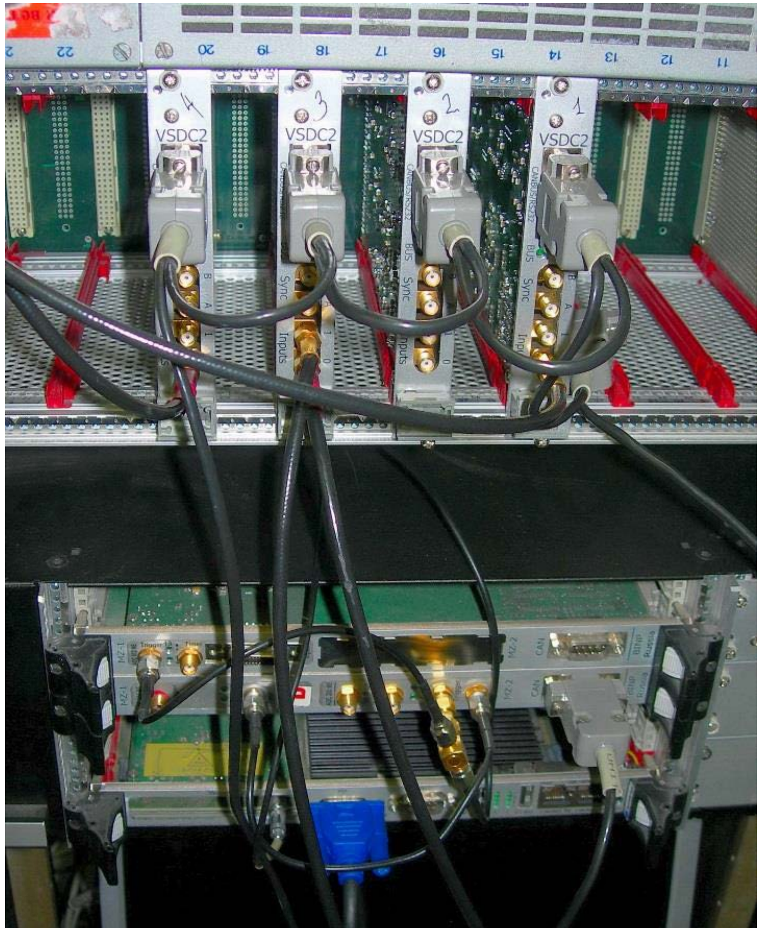
$$\Phi_\Sigma = \frac{\Phi + \Phi}{2} - \Phi = 0$$

$$\Phi_\Sigma = \frac{-3\Phi + \Phi}{2} + \Phi = 0$$

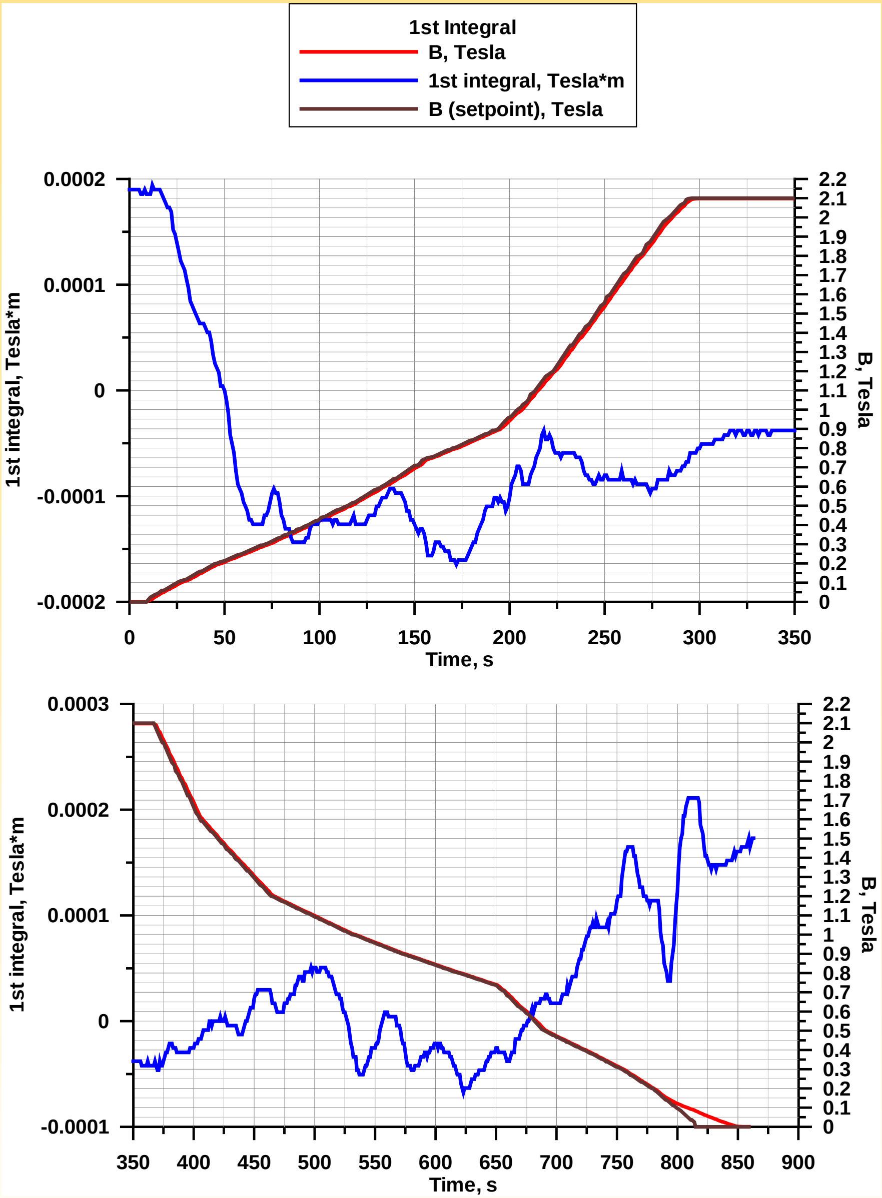
Measurement of pulsed magnets

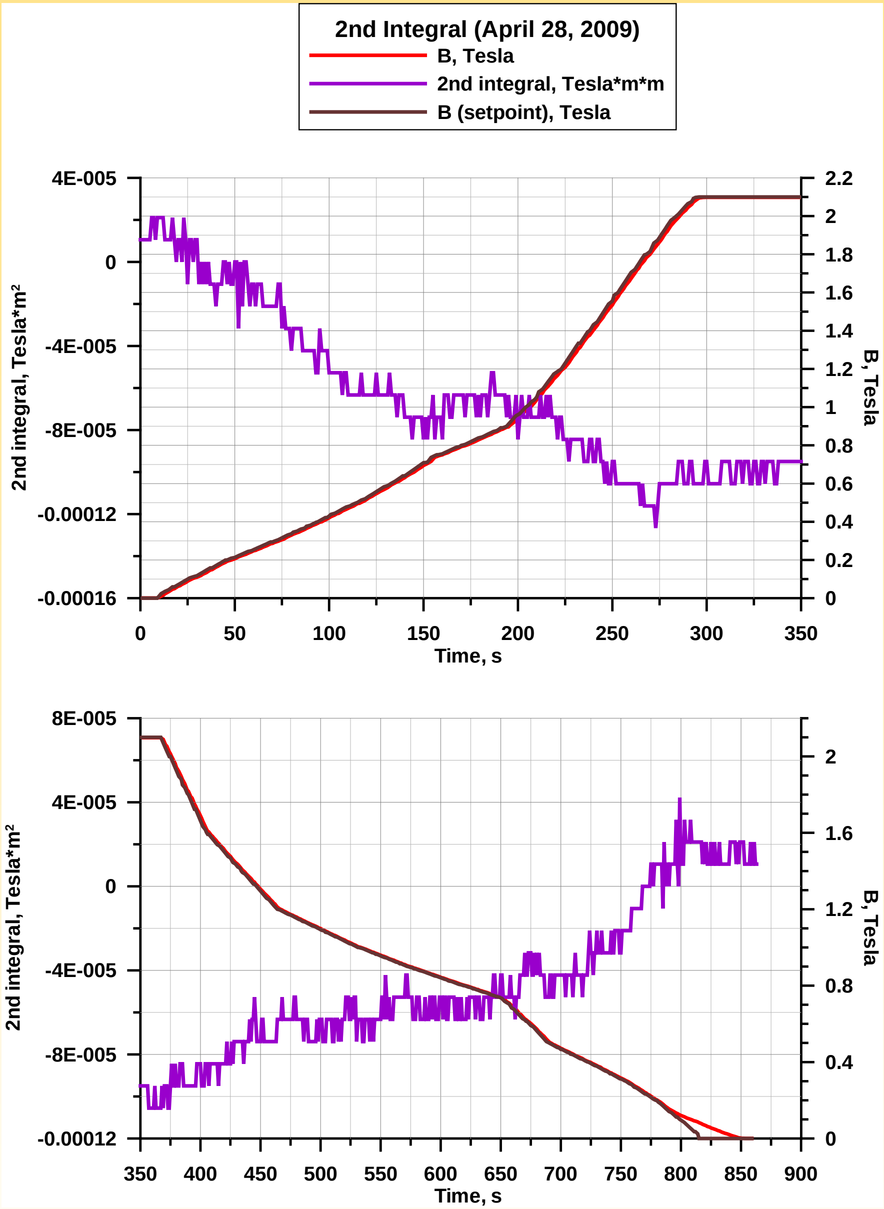




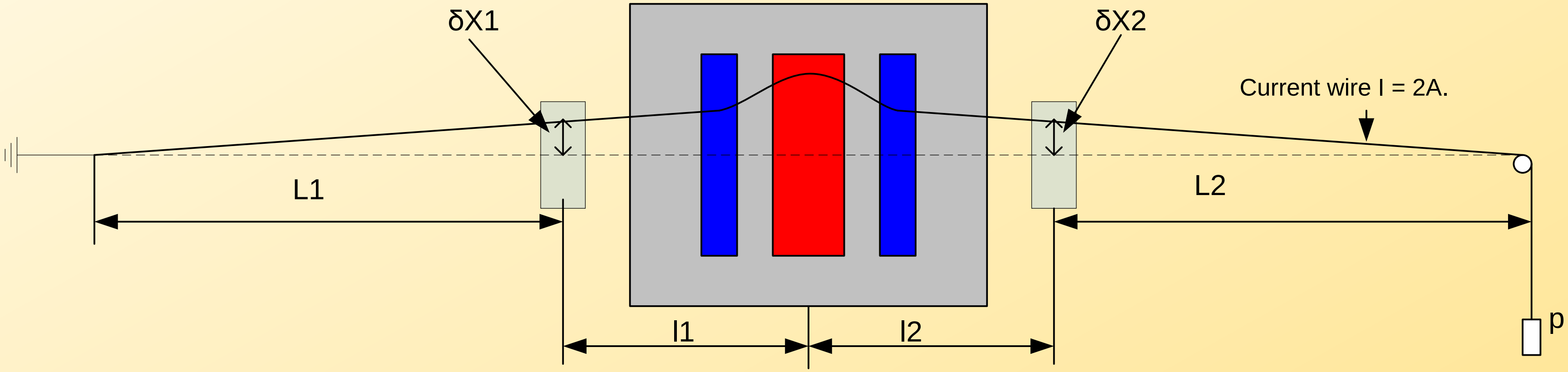


The results of measurements of the magnetic field of the superconducting wiggler





Метод постоянного тока

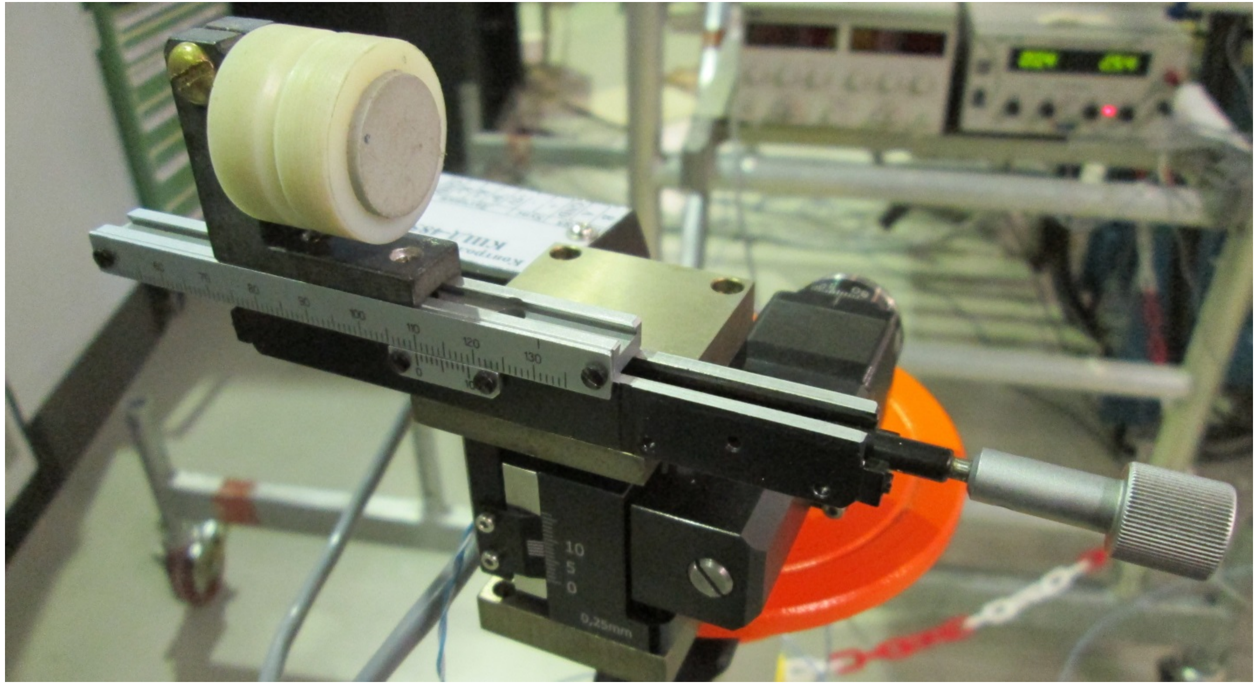


$$I_{first} = I_1\left(\frac{L}{2}\right) = \delta\alpha * \frac{T}{I} = \frac{T}{I}\left(\frac{\delta x1}{L1} + \frac{\delta x2}{L2}\right)$$ -first field integral

$$I_{second} = I_2\left(\frac{L}{2}\right) = \delta x \cdot \frac{T}{I} = \frac{T}{I}(\delta x2 - \delta x1)$$ -- second field integral

+ Одновременное измерение I1, I2
+ Измерение мгновенное с точностью до колебаний проволоки
− Уход нулей
− Невысокая чувствительность
− Нельзя изменять высшие интегралы

Positioning of strings



- Z: “8MVT40-13-1” http://standa.it/
- Motorized (stepping motors)
- 1 step = 0.83 nm
- X: manual, resolution 100 um
- In the wiggler the wire is located in 6 mm diameter tube.