PRECISE MAGNETOMETERS ON BASE OF PULSED NMR TECHIQUES

G.Karpov, A.Medvedko, E.Shubin,

Budker Institute of Nuclear Physics SB RAS,
Novosibirsk, Russia.

Precise Magnetometers on base of pulsed NMR techniques

In 1999-2006 a new generation of precise Magnetometers on base of pulsed NMR techniques has been developed and fabricated at BINP.

Main features:

1) High precision: field measurement error less than 10^{-5}, resolution is of order 10^{-7} (for homogeneous fields)

2) Wide field range: 0.025÷13 T

3) Large field range provided with one probe: B_{MAX}/B_{MIN} is up to 30

4) Acceptable field gradients: grad(B)/B up to 5×10^{-4}/mm

5) Multichannel measurements

6) Small probe dimensions: minimal probe thickness is ~1 mm

7) Small probe sensitive volume – up to 1 mm^3

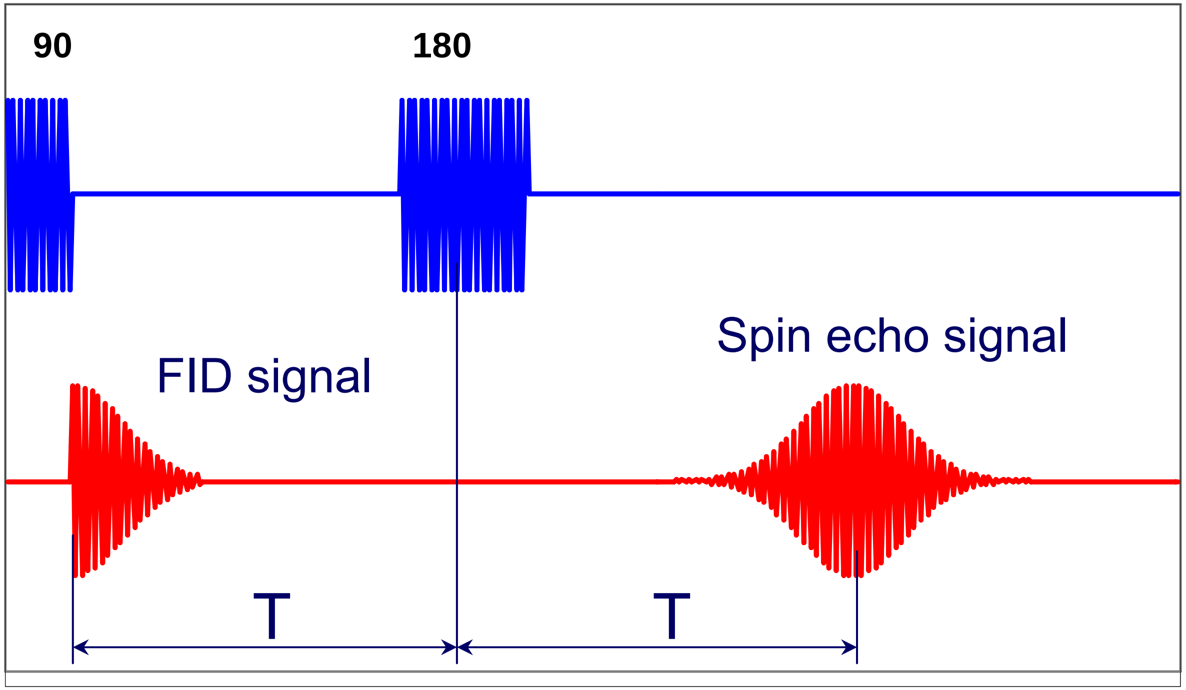
8) Capability of measurements at liquid helium temperature

9) VME standard

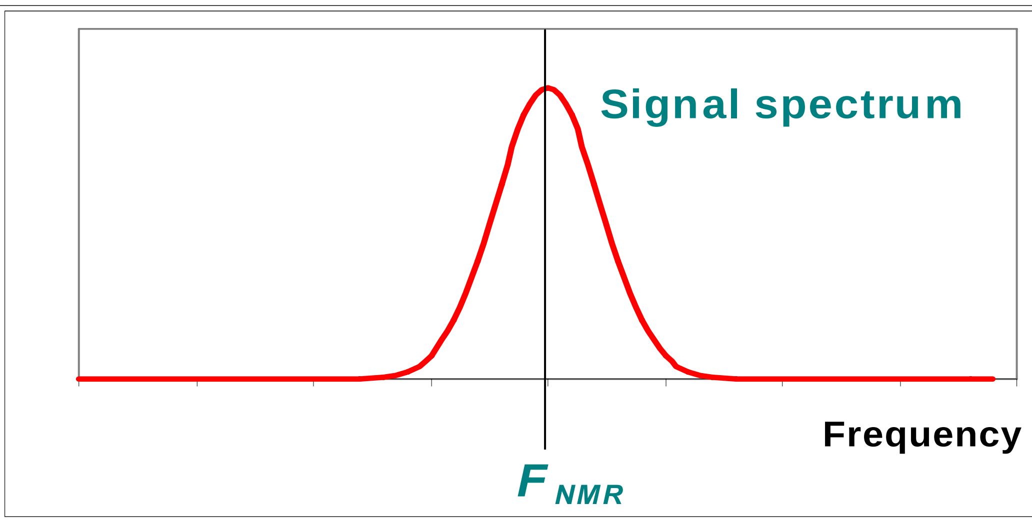
PULSED NMR TECHNIQUE USED IN BINP MAGNETOMETERS

Larmor frequency of nuclear precession $\omega_L = \gamma \cdot B$ ***, where*** **γ – gyromagnetic ratio**

B **– magnetic field value**



If RF pulses frequency F_{RF} is close to precession frequency F_L ($F_{RF} - F_L < 1/T_{90}$) free induction decay (FID) signal and spin echo signal with precession frequency are appeared.

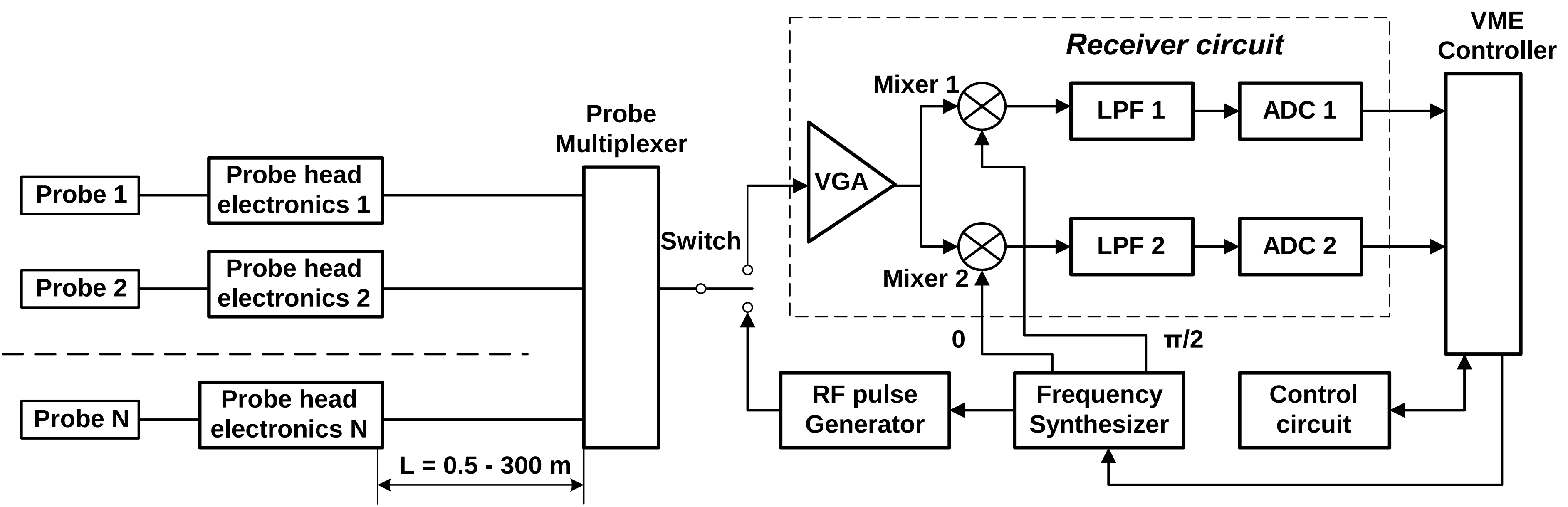


Fourier-transformation

$F_{NMR} = \omega_{L0}/(2\pi)$,

где ω_{L0} ***– precession frequency in the centre of probe sensitive volume***

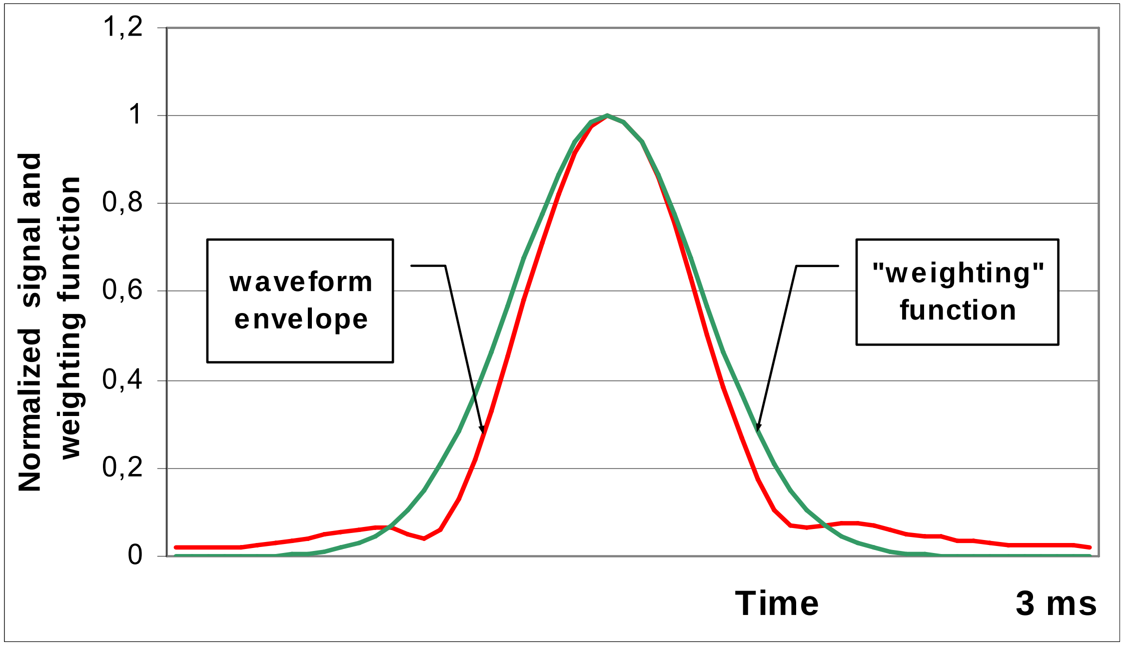
Functional diagram of NMR Magnetometers



Digital signal processing

Purpose: finding of the module and sign of difference frequency $F_D = F_{NMR} - F_{SYNT}$

Matched filtering: signal array before Fourier transformation is multiplied on matched "weighting" function.



Obtained in the magnet EM3.S of VEPP-4M NMR waveform envelope and "weighting" function

Signal-to-noise ratio in frequency domain: $(S/N)^F = \sqrt{E_S/S_N}$

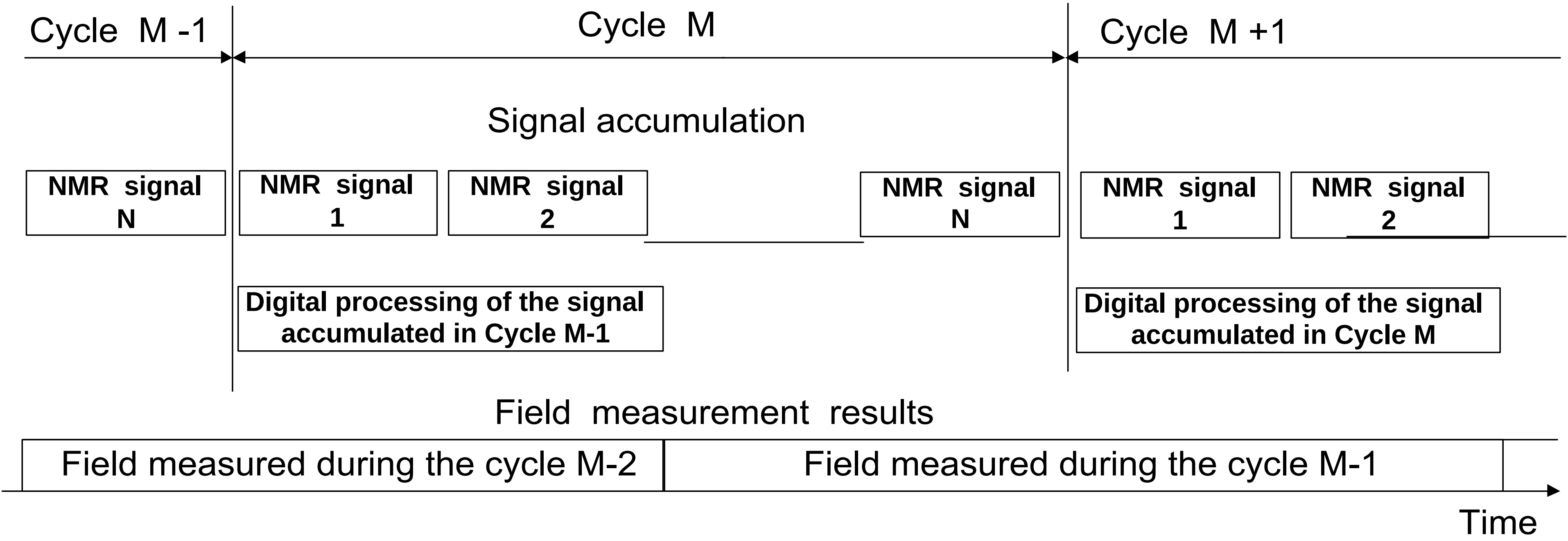
where E_S – signal energy, S_N – noise spectral density

Two modes of operation

1) Search mode: scanning with Synthesizer frequency in specifying range and finding of coarse value of NMR frequency

2) Measurement mode: precise measurement of NMR frequency; Synthesizer frequency is close to NMR frequency and follows to it

Measurement cycle structure



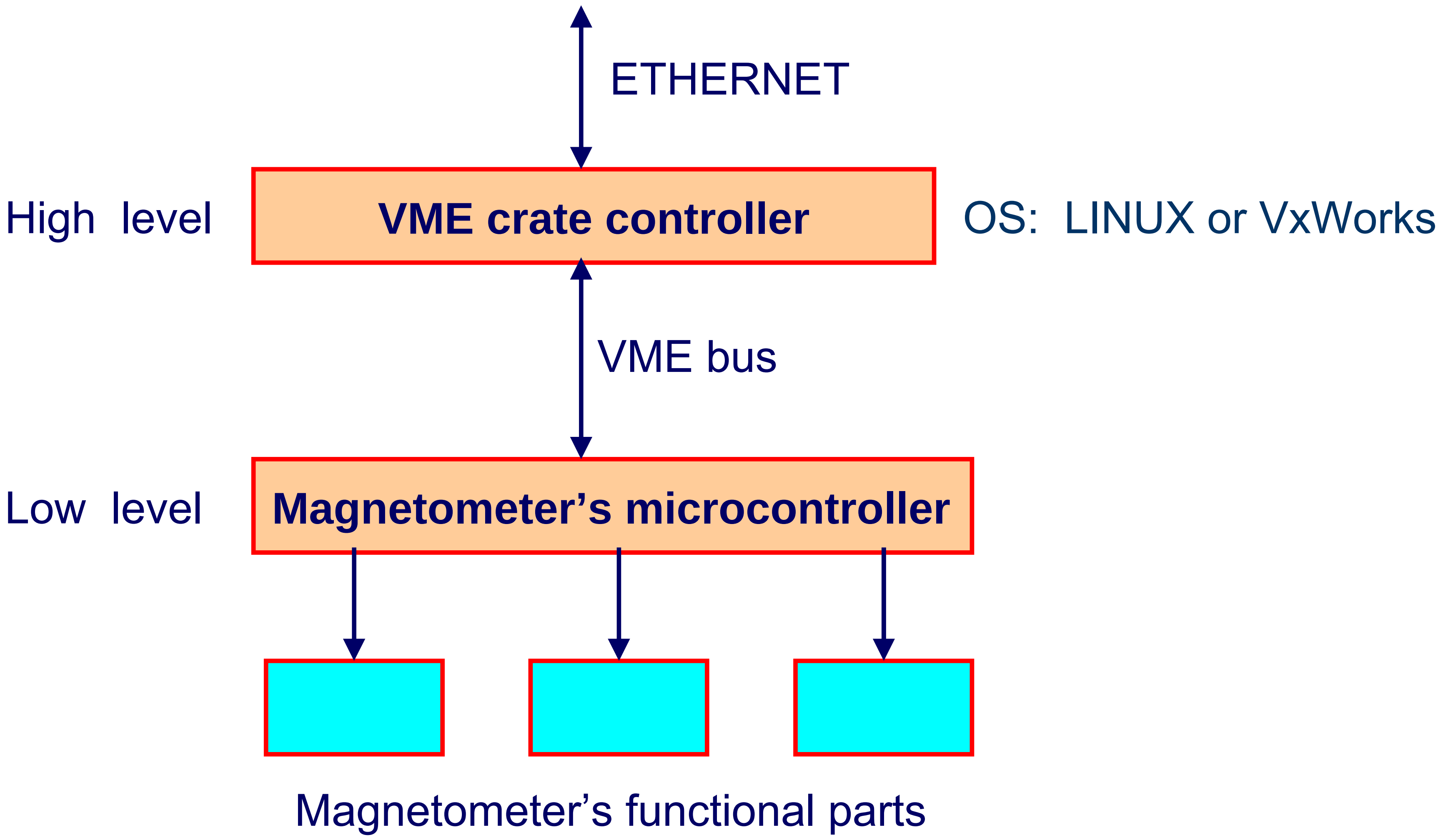
During the measurement cycle signal accumulation is performed: summing of *N* registered NMR signals (digit arrays). It follows to signal-to-noise ratio increasing in $\sqrt{N}$ times.

Simultaneously with signal accumulation digital signal processing is performed. During the cycle *M* digital processing of the signal accumulated in cycle *M-1* is performed.

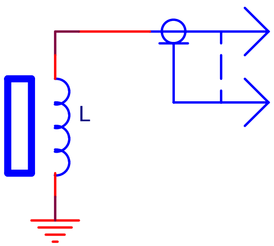
Time duration of the elementary cycle T_C = 20÷100 ms

Number of accumulated signals N = 10÷100

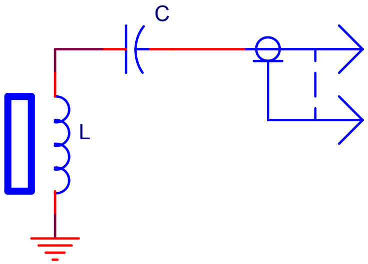
Structure of the Magnetometer’s Control System

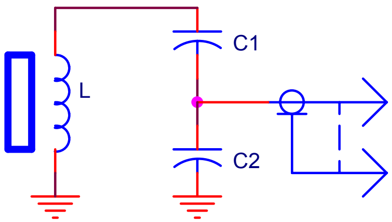


NMR probes



wide range
NMR probe



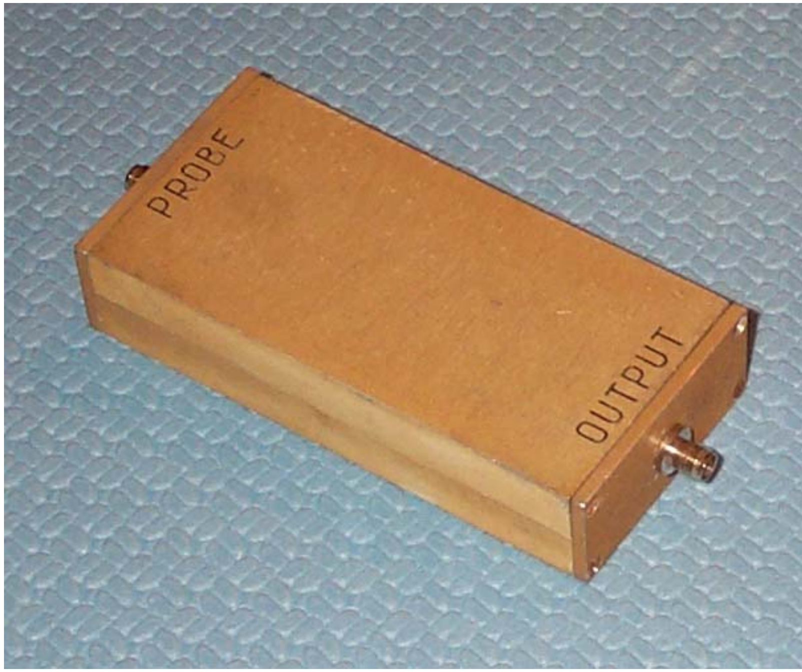


Resonant NMR probes

Miniature NMR probes – with thickness up to 1 mm.

Probes with small sensitive volume – up to 1 mm^3.

Probe Head electronics

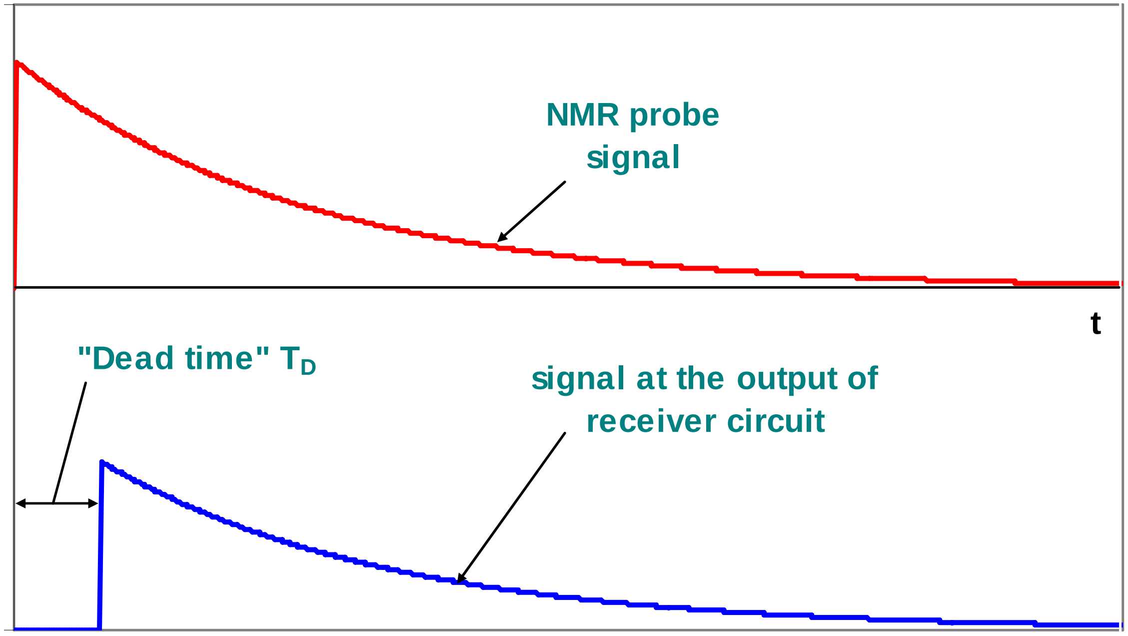


One of NMR Probe design

Parameters of working substances

Working substance	Working nuclei	Gyromagnetic ratio (with “chemical shift”) *γ/(2π), MHz/T*	Spin-lattice relaxation time T_1, *ms*	Spin-spin relaxation time T_2, *ms*
water	protons	42.576396	5÷3000	5÷3000
rubber	protons	42.576268	~20 *(B=0.5T)*	~0.7
Lithium salts solution	^{7}Li nuclei and protons	16.54646	~1000	~1000
“heavy” water	deiterium	6.53569	~1000	~1000
Metal aluminium powder	^{27}Al nuclei	11.112	~30 *(T=4.2K)*	~0.04
Teflon	^{19}F nuclei	40.0546	~40	~0.09

“Dead” time of the Magnetometer’s receiver circuit.

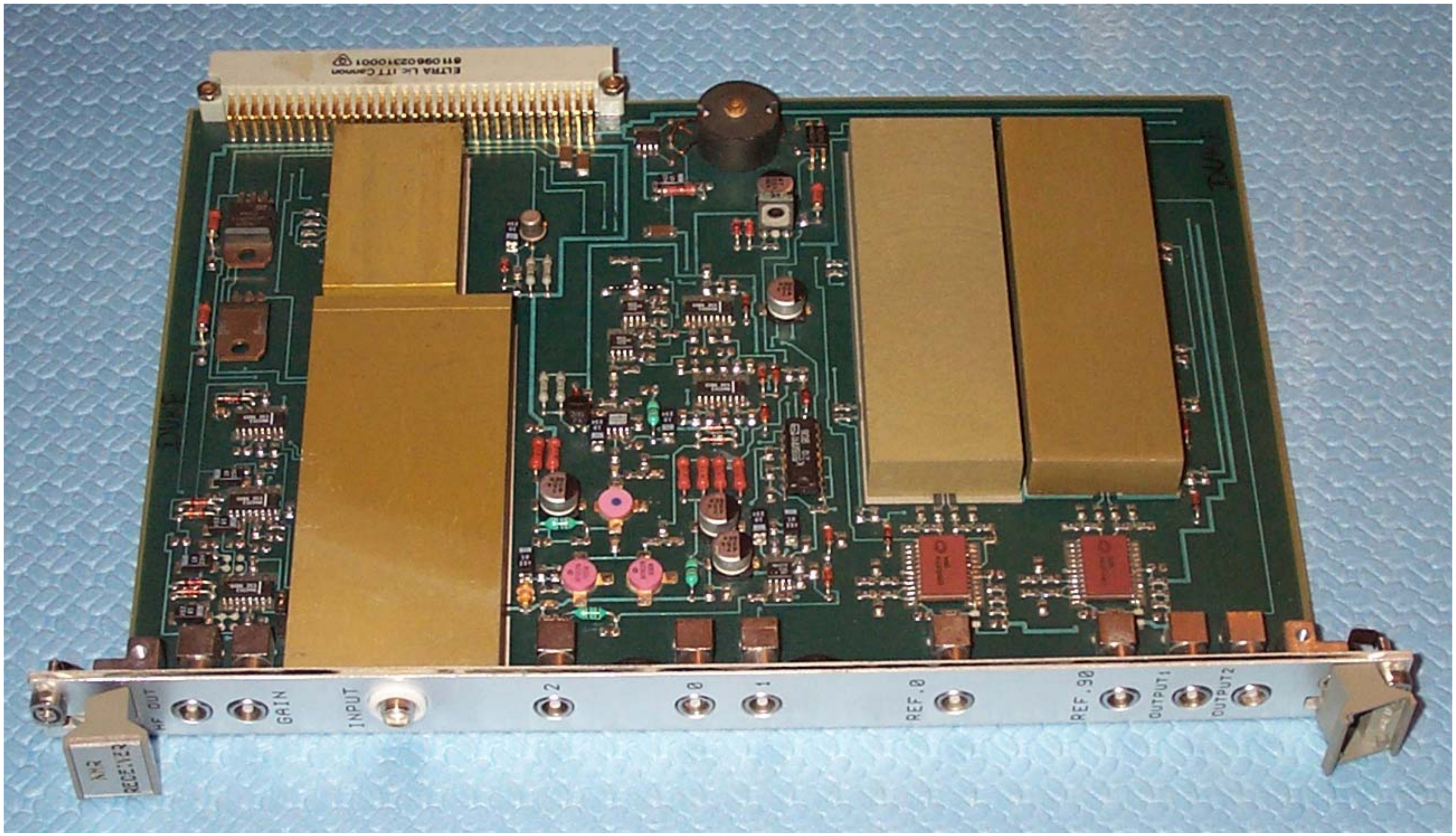


The problem of “dead time” decreasing is connected with large difference between RF pulses amplitude (~20V) and NMR signal amplitude (a few μV).

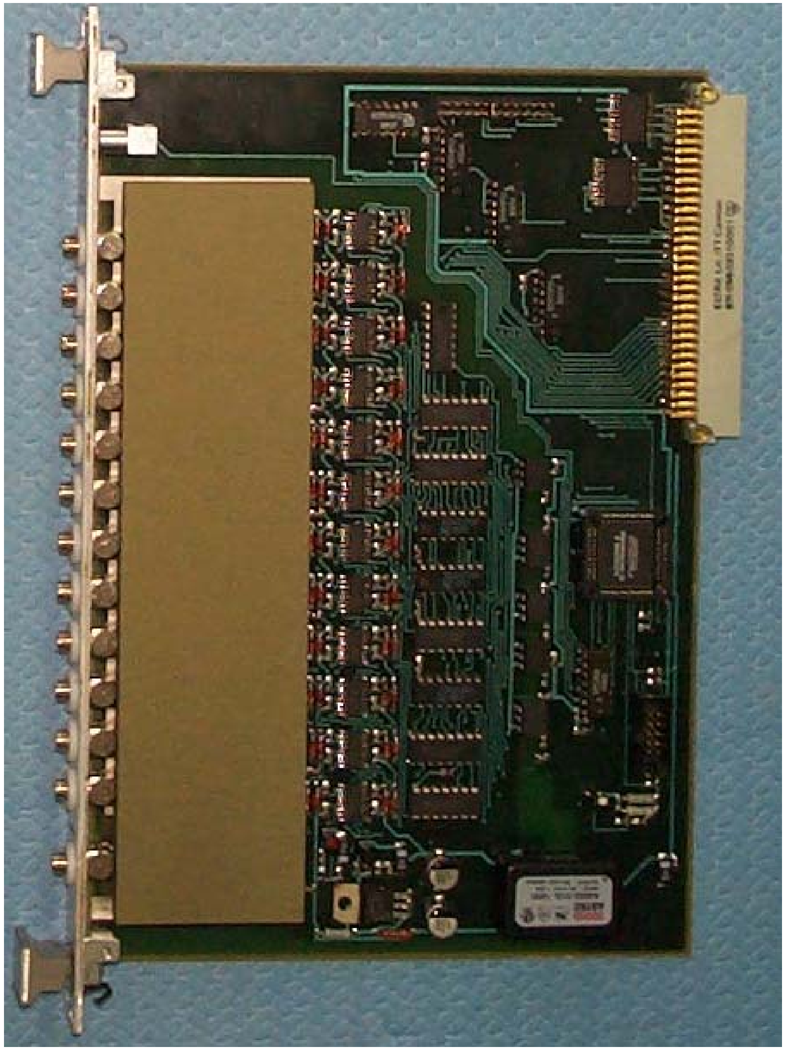
Two modifications of NMR Magnetometers:

Modification	*“Dead time”* T_D	*Range of NMR signal duration*
1	~100 μs	0.5÷100 ms
2	3÷5 μs	10÷1000 μs

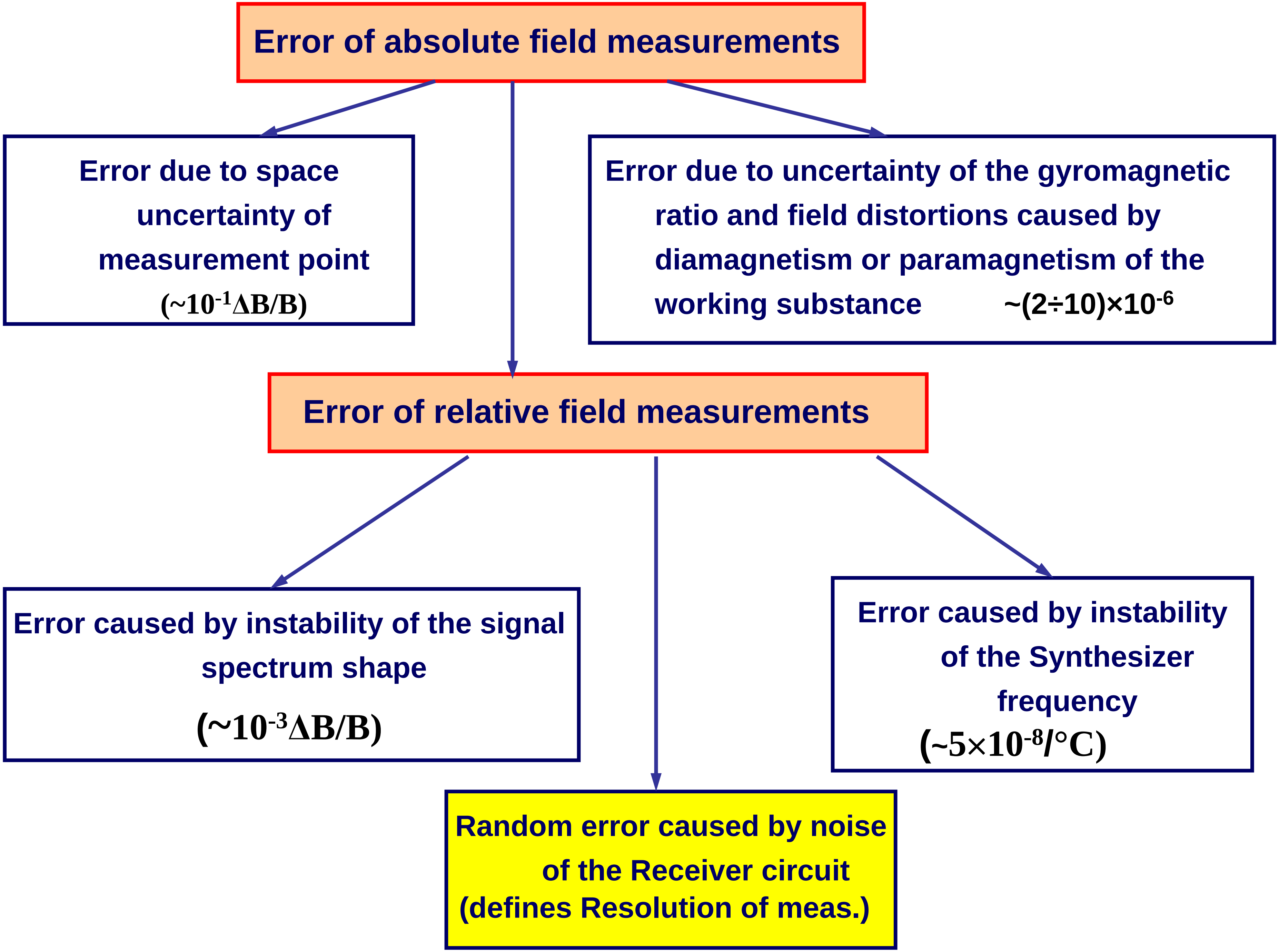
Receiver module



12-channel Probe Multiplexer



12-channel Magnetometer in VME standard



Error of absolute field measurements
Error due to space uncertainty of measurement point
$(\sim 10^{-1}\Delta B/B)$
Error due to uncertainty of the gyromagnetic ratio and field distortions caused by diamagnetism or paramagnetism of the working substance
$\sim(2\div10)\times10^{-6}$
Error of relative field measurements
Error caused by instability of the signal spectrum shape
$(\sim 10^{-3}\Delta B/B)$
Error caused by instability of the Synthesizer frequency
$(\sim 5\times10^{-8}/°C)$
Random error caused by noise of the Receiver circuit
(defines Resolution of meas.)

RMS frequency measurement error, caused by noise

$$\sigma_F \cong \frac{\Delta F_S}{(S/N)^F}$$

where $(S/N)^F$ **– signal-to-noise ratio in frequency domain,**

ΔF_S **– width of the signal spectrum.**

Width of the signal spectrum:

$$\Delta F_S \cong \Delta F_0 + \frac{\gamma}{\pi} \cdot \Delta B \cong 1/T_2 + \frac{\gamma}{\pi} \cdot \Delta B$$

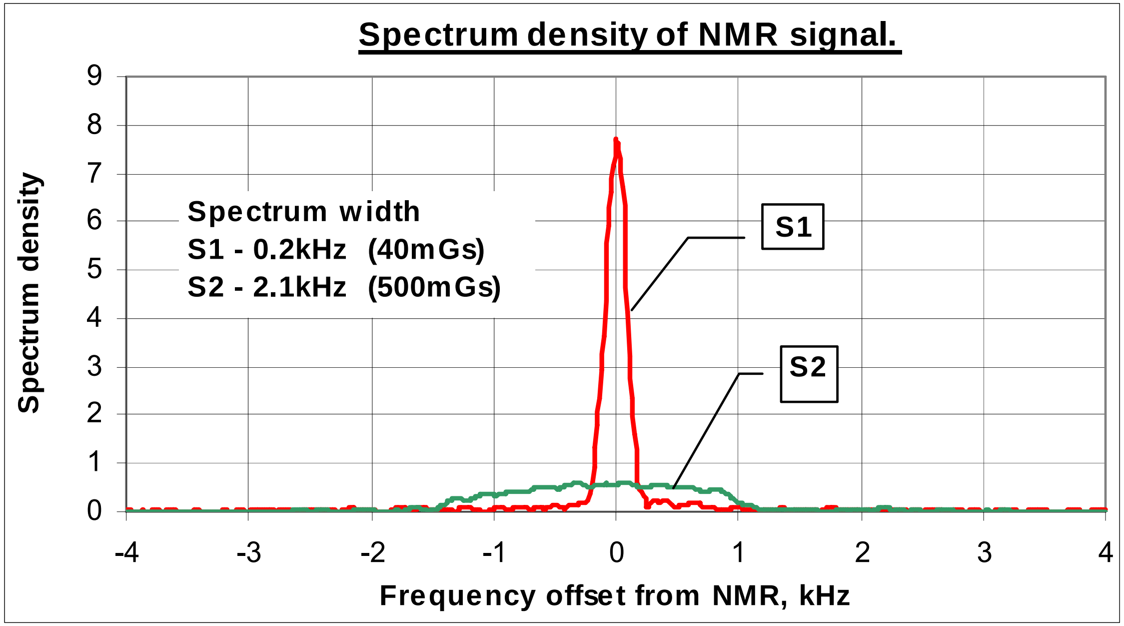
where ΔF_0 **– working substance NMR linewidth**

T_2 **– spin-spin relaxation time of working substance**

ΔB **– field dispersion within probe sensitive volume**

γ **– gyromagnetic ratio**

Dependence of σ_F on the width of NMR signal spectrum



NMR signal spectrums obtained with the same probe at the fields with different gradient
$Grad(B)_1 \approx 0.1 \cdot grad(B)_2$

Minimizing of the signal spectrum width:

1) NMR probe has to be set in the region with most homogenous field
2) In some cases – using of the compensating coils
3) Optimal probe sensitive volume (corresponds to condition: $1/T_2 \cong k \cdot \Delta B \cdot \gamma/\pi$)

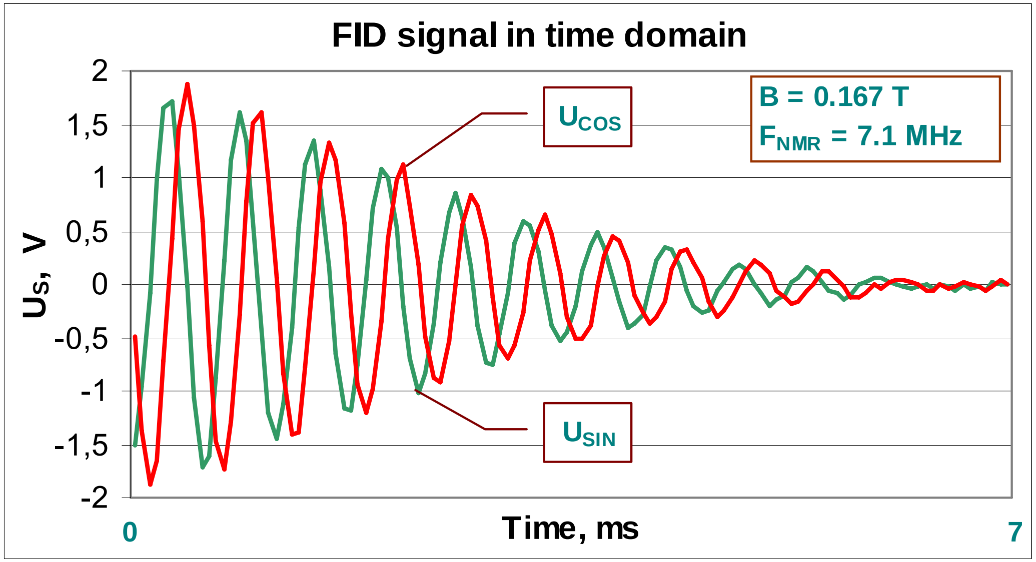
Resolution of measurements of the field with grad(B)/B less than 10^{-5}/mm in the range 0.1÷13 T is of order $10^{-7}/\sqrt{Hz}$ (for the probes on base of aluminium is of order $10^{-6}/\sqrt{Hz}$)

NMR Magnetometer for electron-positron storage ring VEPP-4 (BINP)

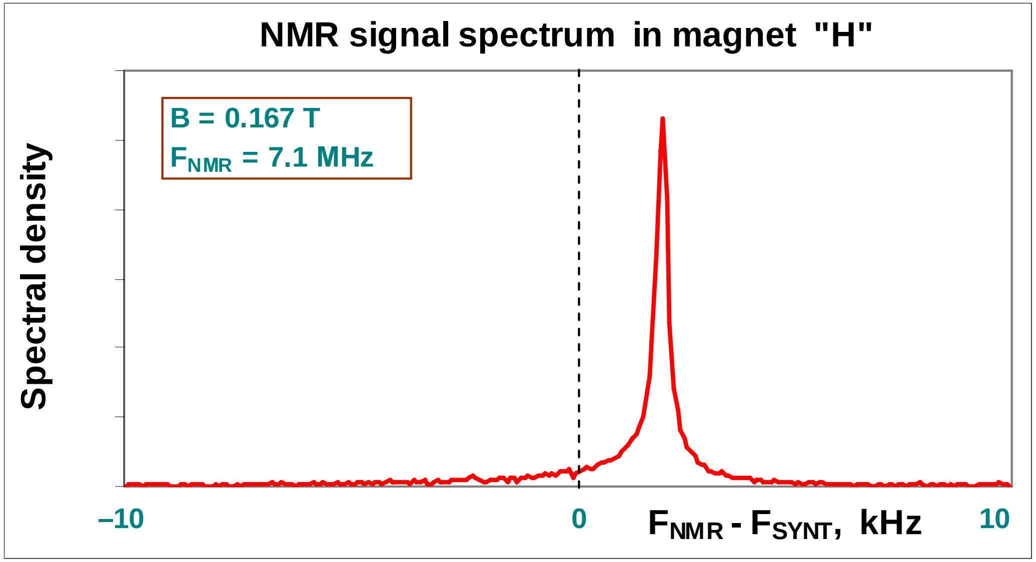
Magnetometer is used for field measurements of four different bending magnets in the ring and one additional magnet (magnet “H”) connected in series with main bending magnets of the ring.

Field range of VEPP-4 magnets

Magnet	H	NEM.1	SEM.1	SIM.3	EM3.S
Field range, T	0.1÷0.6	0.15 ÷0.8	0.15 ÷0.8	0.15 ÷0.8	0.15 ÷0.9



FID signal in time and frequency domain obtained in magnet “H” on the field 0.167 T (beam energy - 1840 MeV).



Relative width of signal spectrum:

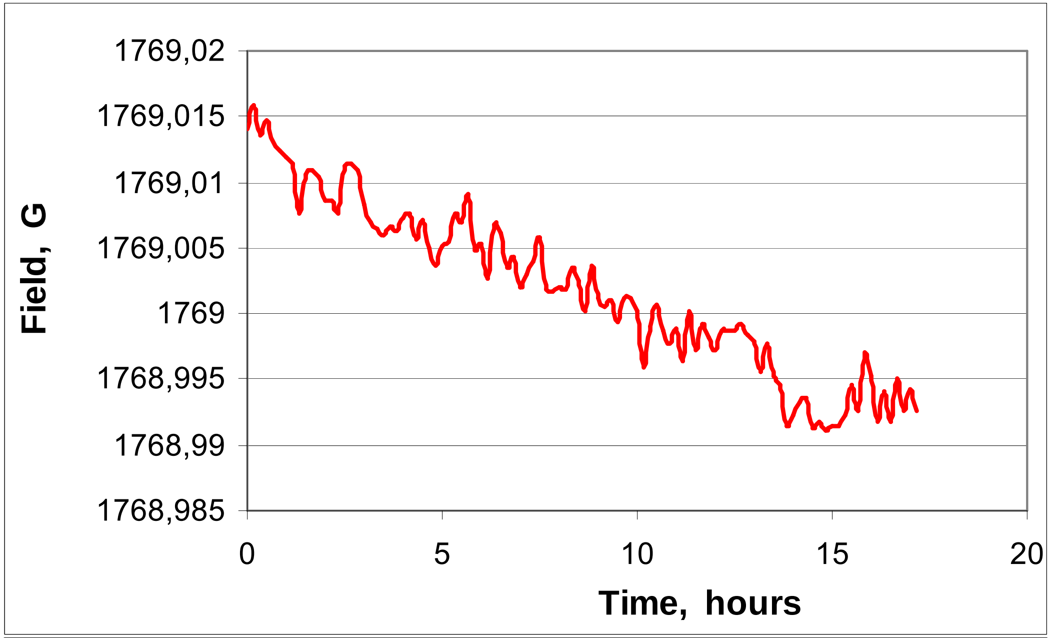
$\Delta F_S / F \approx 3\times10^{-5}$

Signal-to-noise ratio in frequency domain for measurement time 1 s:

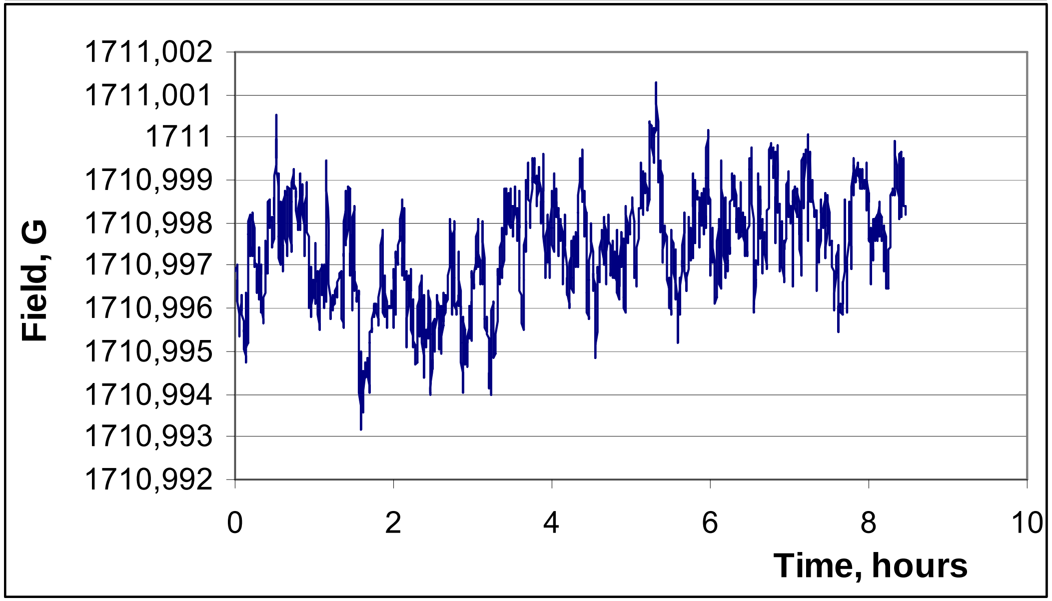
S/N ≈ 500

Resolution of measurements $\sigma_F / F_{NMR} \approx 10^{-7} / \sqrt{Hz}$

Results of field monitoring of the magnet "H" (VEPP-4)



Field of the magnet "H" before experiments

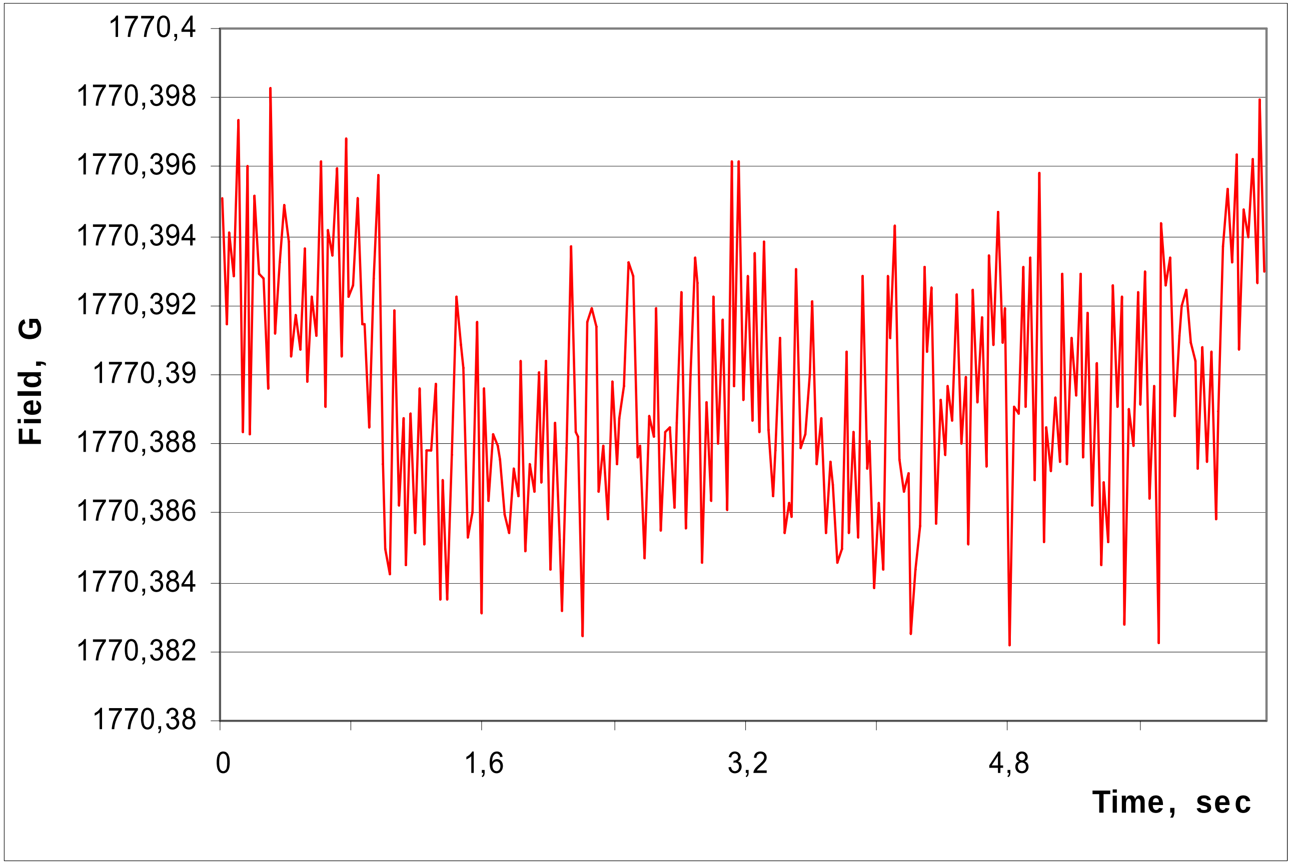


Field of the magnet "H" during experiments

Time of one measurement ~2 sec

$\sigma_F / F_{NMR} \approx 5 \times 10^{-8}$

Fast NMR measurements at VEPP-4



Field measurement results of magnet "H"

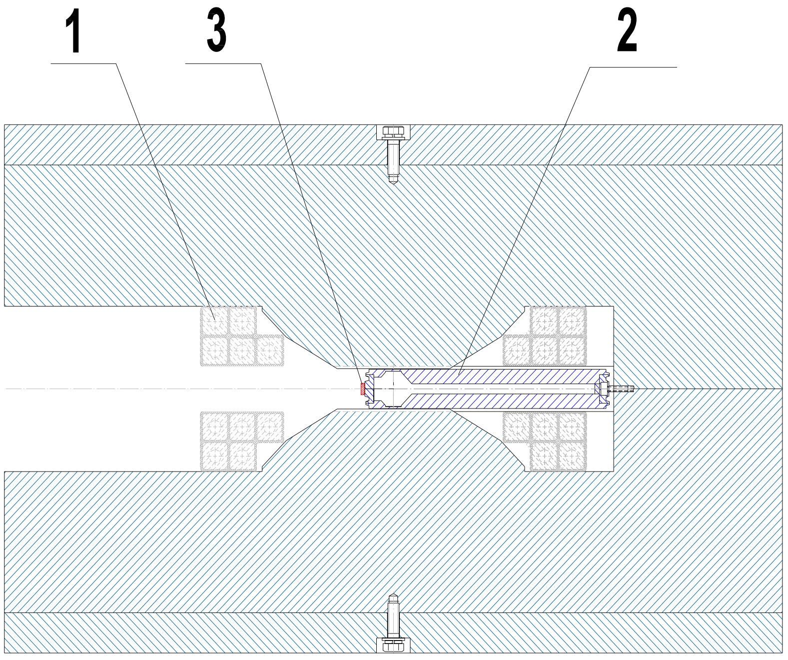
Time of one measurement ~50 ms (without signal accumulation)

$\sigma_F / F_{NMR} \approx 4 \times 10^{-7}$

NMR Magnetometer for electron-positron collider VEPP-2000 (BINP)

NMR probes are set at all eight bending magnets of the ring.

Main problem: Large field gradient within the probe volume – up to 120 G/cm at maximal field ~2.4 T (Beam energy ~1 GeV).



Position of NMR probe in the gap of VEPP-2000 bending magnet:

1 – magnet coil,

2 – vacuum chamber,

3 – NMR probe.

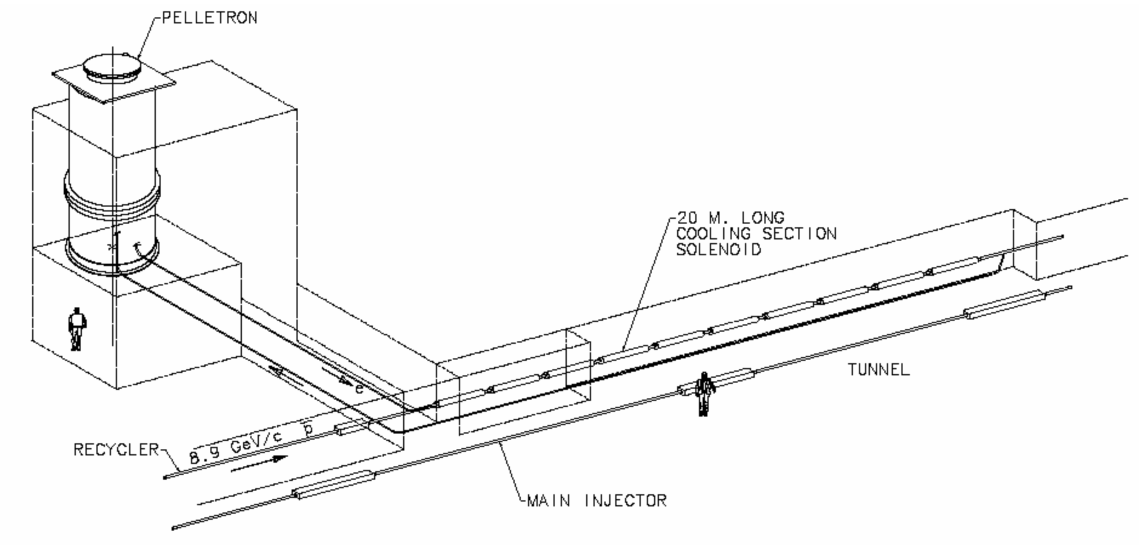
NMR probe with rubber working substance sample 0.3×1.2×3 mm

Width of the signal spectrum in the field range 0.3÷2.4 T is $(1\div2)\times10^{-4}$

Resolution is better than $10^{-5}/\sqrt{Hz}$

NMR Magnetometer for electron cooling facility (Fermilab, USA)

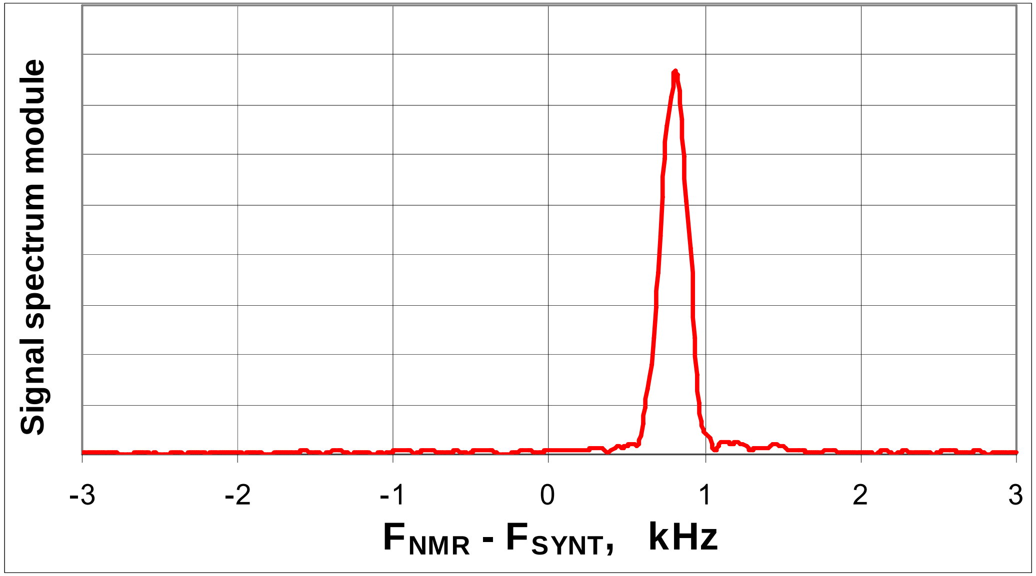
NMR Magnetometer is used for field stabilization of ten bending magnets of electron transport system.



Layout of the electron cooling facility

Bending magnets of the electron transport system

Parameter	***Units***	***Value***	
Magnet type	**–**	**45-degree**	**90-degree**
Number	**–**	**8**	**2**
Nominal field	***G***	**320**	**450**
Field range	***G***	**270÷370**	**400÷500**



NMR signal spectrum in the field 320 G of the 45-degree magnet ***(F_{NMR} = 1.36 MHz)***

Parameters of the signal spectrum:

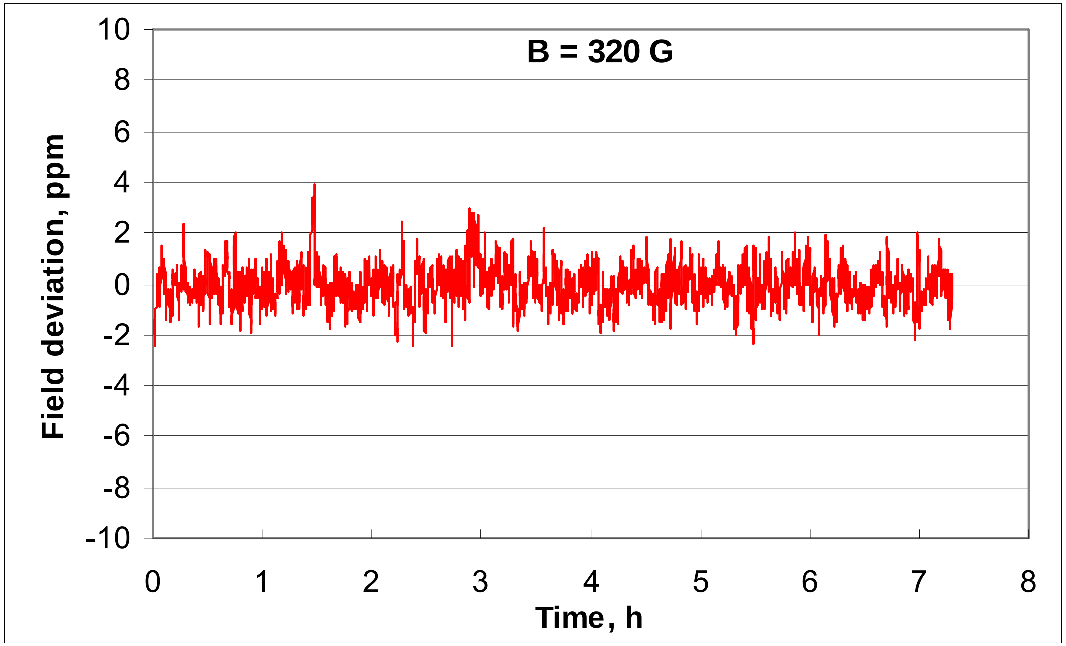
- Relative width ~10^{-4}
- Signal-to-noise ratio (*measurement time is 1 sec)* ~ 250

Resolution: $\sigma_F / F_{NMR} \approx 3\times10^{-7}/\sqrt{Hz}$.

Maximal error of relative field measurements:

~2×10^{-6} – for year

Field stabilization on base of NMR magnetometer



Results of field stabilization of 45-degree bending magnet (obtained with another NMR Magnetometer)

At present all 10 bending magnets of the transport system are stabilized.

Long-time field stability is ~10^{-5} and limited by 16-bit Power Supplies DACs.

Position of NMR Magnetometer at MI-31 (Fermilab)

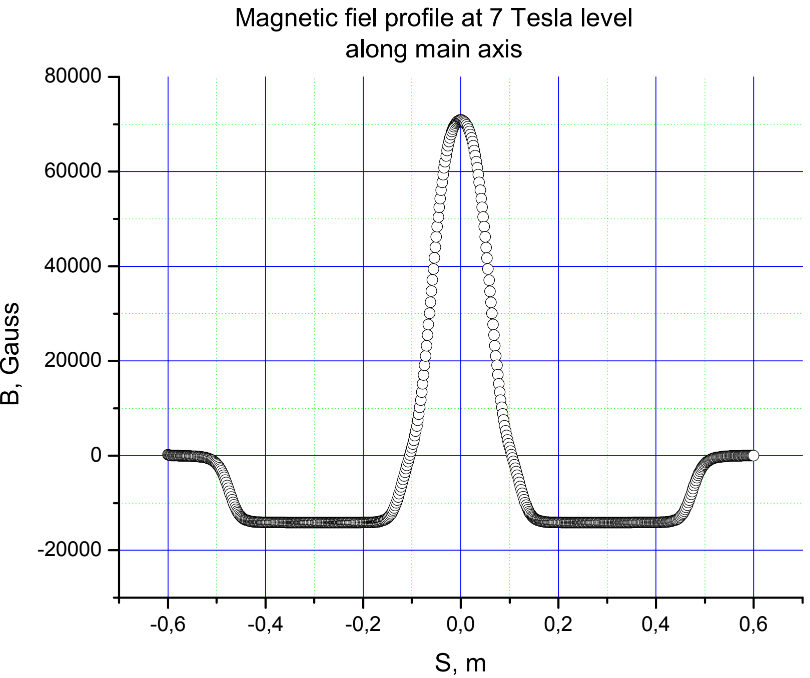
VME crate with NMR

Field measurements with NMR magnetometer at liquid helium temperature

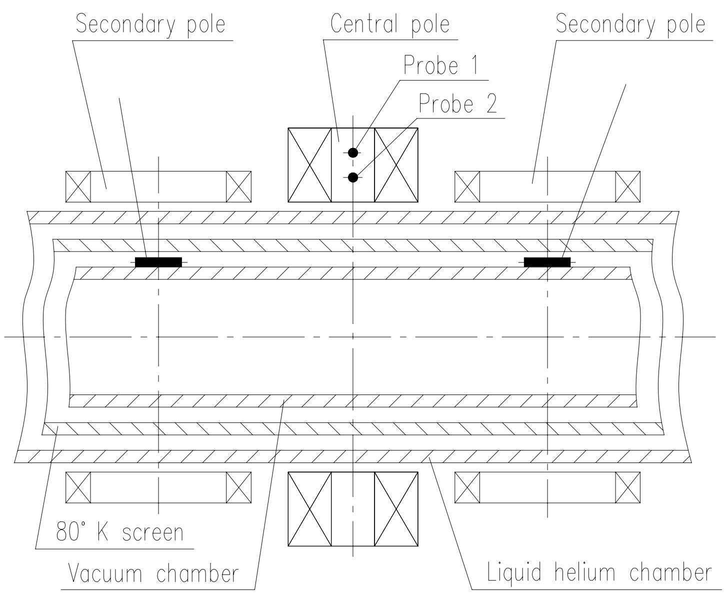
One of the tasks is magnetic field measurements in the superconducting 3-pole Wave Length Shifters (WLS).

Task: measurements of the WLS central pole field with precision of order 10^{-5}.

Field range: 3÷7 T for BESSY-2 WLS and 5÷10 T for SpRing-8 WLS.



Field along WLS central axis measured with Hall probes

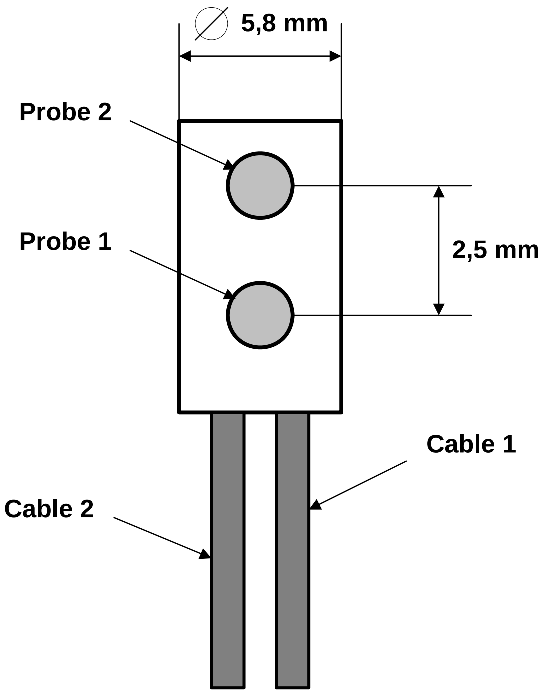


Position of NMR probes inside the WLS.

NMR Probes for WLS

Assembling of pair NMR probes is set in the central pole axis in the hole of 6mm diameter.

Probe working substance – aluminium powder, sensitive volume ~2 mm^3.

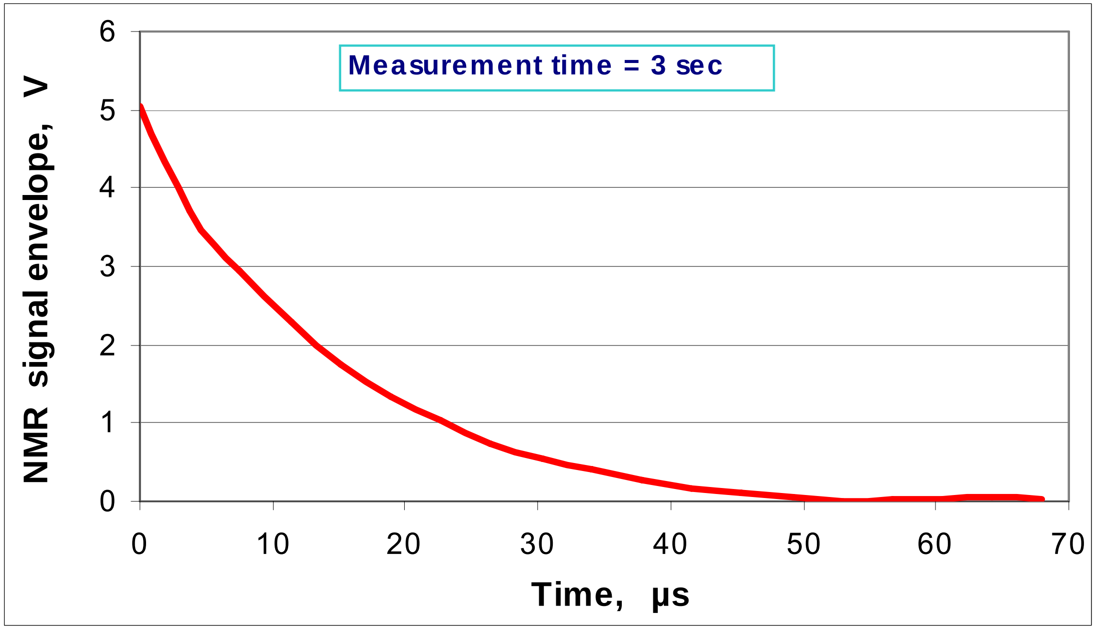


Design of NMR probes assembling.

Assembling of the pair of NMR probes.

Resolution of measurements of WLS field

Nuclear magnetization M_N is proportional to $1/kT$, where T – is temperature.
At liquid helium temperature ($T \approx 4.1K$) M_N is increased in 70 times compare with room temperature.



NMR signal at the WLS central pole field ~6 T ($F_{NMR} \approx 58$ МГц)

Signal-to-noise ratio ~ 600

Relative width of the signal spectrum $\sim 6 \times 10^{-4}$

Resolution of measurements $\sim(1\div2)\times10^{-6}/\sqrt{Hz}$

Conclusion

In 1999-2006 ten NMR Magnetometers on base of pulsed techniques have been fabricated and applied at charge particles storage rings and field measurements stands at:

- BINP (Russia)
- Fermilab (USA)
- Duke University (USA)
- BESSY-2 (Germany)
- SpRing-8 (Japan)

At present new NMR Magnetometer in VME standard is developing:

- **one-channel magnetometer will occupy one VME module**
- **all digital signal processing will be performed by this module**

The end

ЯМР магнитометры, разработанные в России и за рубежом

Изготовитель	Параметр								
	Диап. полей, *T*	Миним. толщ. датчика	$\frac{B_{max}}{B_{min}}$	V_{min} *мм*^{3}	Темпе-ратура	Ср.кв. погр. $(\sigma_F)_1/F$	Неста-бильн. част.	δ_{OTH} за сутки	Макс. град. G/B
ИЯФ СО РАН	0.025÷13	0.55 *мм*	40	1	Комн., *4 К*	10^{-7}÷10^{-8}	5×10^{-8}/°C	4×10^{-7}	5×10^{-3}/см
Metrolab Instrument, Швейцария	0.043÷14	~3 *мм*	3	10	Комн.	3×10^{-7} T	5×10^{-9}/°C	10^{-7}	2×10^{-3}/см
Drusch, Германия	0.02÷9	~5 *мм*	5	20	Комн.	10^{-7} T	10^{-6}/год	10^{-7}	–
Virginia Scientific Instrument, США	10^{-6} ÷ 2.2	~2 *мм*	2×10^{6}	10	Комн.	10^{-7}	2×10^{-8}/год	3×10^{-7}	–
ОИЯИ, Дубна	0.04÷6	–	2	–	Комн.	–	–	10^{-6}	5×10^{-3}/см
Лаборатория PTB, Германия	0.05÷2	–	–	–	Комн.	10^{-7}÷10^{-8}	–	–	–
Университет Гейдельберга, Германия	1.5÷1.7	~5 *мм*	–	–	Комн.	3×10^{-9}	10^{-10}/год	10^{-8}	–
Швейцарский Федеральный Институт Технологии	0.7÷7	~1 *мм*	10	1	Комн.	10^{-7}	–	–	–

Максимальная погрешность относительных измерений поля (за сутки) для двух случаев

1) Измерения поля калибровочного магнита стенда магнитных измерений ИЯФ нерезонансным датчиком с объемом рабочего вещества (воды) около 4 мм³. В диапазоне полей 0.5÷1.8 Т :

$$\delta_{OTH} \cong (1 \div 3) \times 10^{-8} / \sqrt{T_И} + (3 \div 5) \times 10^{-9} + (5 \times 10^{-8} \cdot \Delta T_O + 3 \times 10^{-8})$$

$\delta_{Ш}$ $\delta_{СП}$ $\delta_{СИНТ}$

где $T_И$ – полное время одного измерения.

С учетом нестабильности частоты Синтезатора: $\delta_{OTH} \approx 5 \times 10^{-7}$ **, ($\Delta T_O = 10°C$).**

***Без учета нестабильности частоты Синтезатора*:** $\delta_{OTH} \approx (1 \div 2) \times 10^{-8}$ **.**

2) Измерения поля сверхпроводящего соленоида при температуре жидкого гелия датчиком с объемом рабочего вещества (порошка алюминия) около 2 мм³. В диапазоне полей 5÷13Т :

$$\delta_{OTH} \cong (0.5 \div 1) \times 10^{-6} / \sqrt{T_И} + (2 \div 4) \times 10^{-7} + (5 \times 10^{-8} \cdot \Delta T_O + 3 \times 10^{-8})$$

$\delta_{OTH} \approx (1 \div 2) \times 10^{-6}$ **(ΔT_O = 10гр.).**

Максимальная погрешность относительных измерений поля калибровочного магнита

При использовании нерезонансного датчика с объемом рабочего вещества (воды) около 4 мм^3 в диапазоне полей 0.5÷1.8 Т величина δ_{OTH} (за сутки) :

$$\delta_{OTH} \cong (1 \div 3)\times 10^{-8} / \sqrt{T_{И}} + (3 \div 5)\times 10^{-9} + (5\times 10^{-8} \cdot \Delta T_{O} + 3\times 10^{-8})$$

$\delta_{Ш}$ $\delta_{СП}$ $\delta_{СИНТ}$

где $T_{И}$ – полное время одного измерения,

ΔT_{O} – изменение температуры окружающей среды.

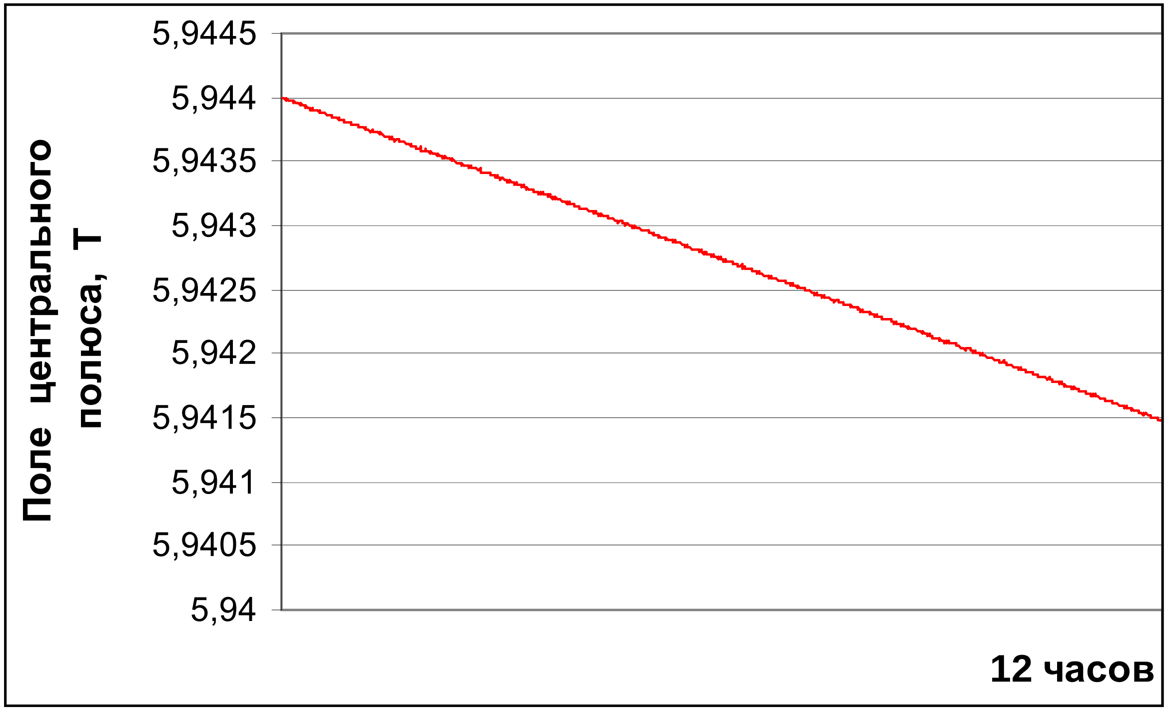
При времени одного измерения $T_{И}$ = 2 сек:

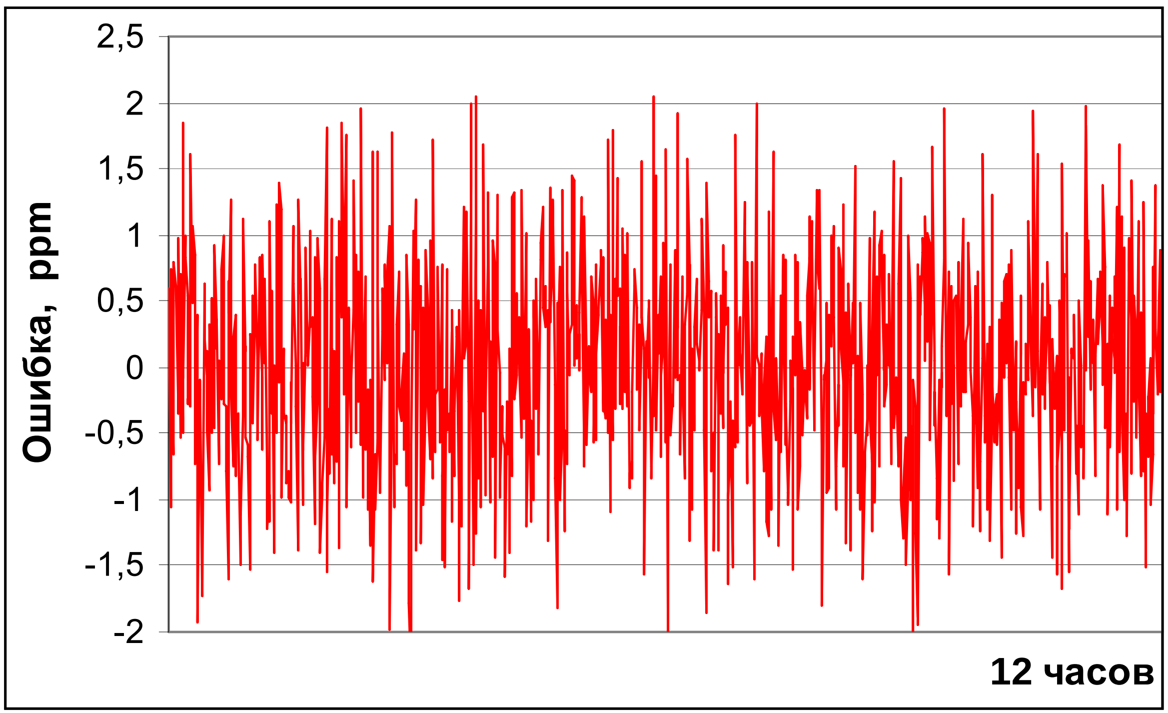
Без учета нестабильности частоты Синтезатора: $\delta_{OTH} \approx (1 \div 2)\times 10^{-8}$.

С учетом нестабильности частоты Синтезатора:

$\delta_{OTH} \approx 0.5\times 10^{-7} + 5\times 10^{-8} \times \Delta T_{O}$ – за сутки;

$\delta_{OTH} \approx 10^{-6} + 5\times 10^{-8} \times \Delta T_{O}$ – за год





Результаты измерения естественного спада поля центрального полюса вигглера в режиме Persistent Current Mode.

Всего выполнено около 1000 измерений за 12 часов

Постоянная времени спада поля – около одного года

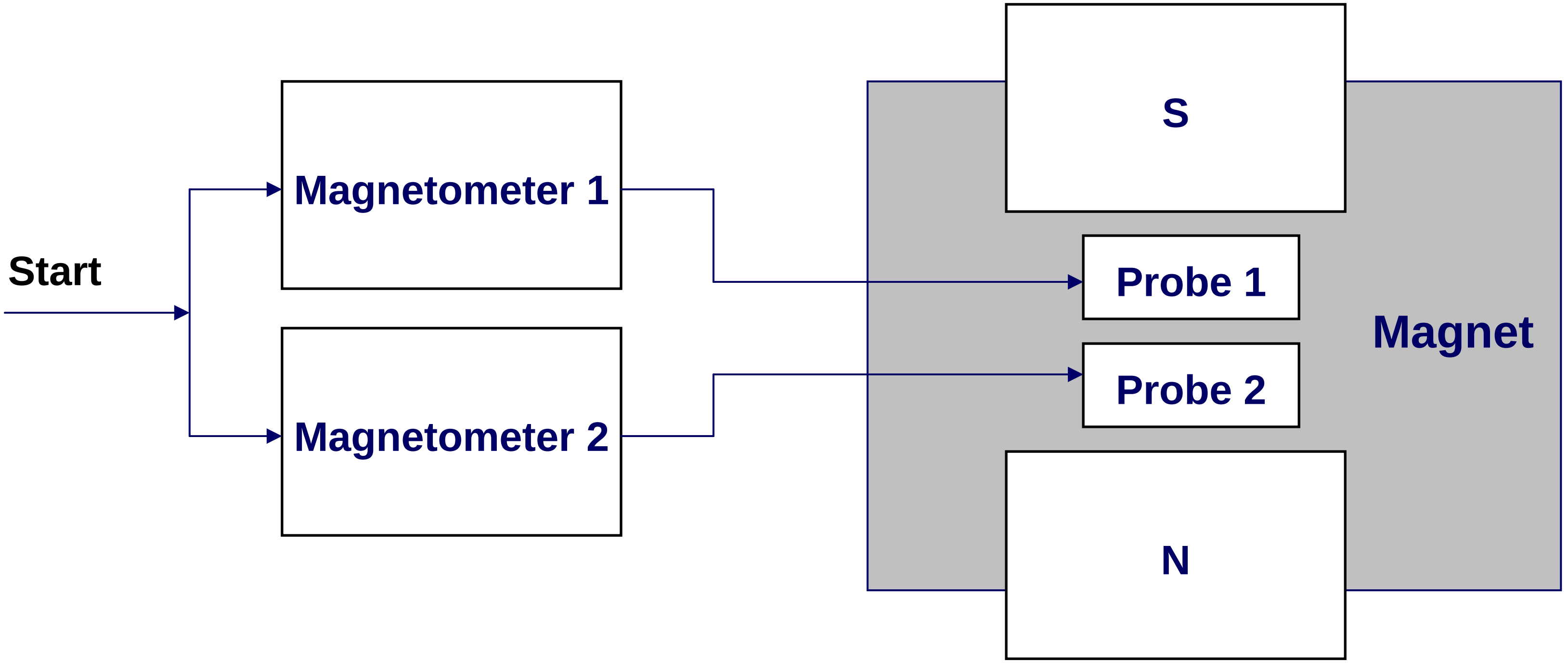
Погрешность измерения поля,вызванная шумами, для каждого из выполненных измерений.

$\sigma_F / F \approx 0.7 \times 10^{-6}$

Two methods of the Resolution value measurement

1) **Indirect method – on base of measured values of the NMR signal and noise**

2) **Direct method – by using of two NMR Magnetometers**



A few thousands field measurements are performed. Resolution is calculated on base of differences of two Magnetometers results.