PRECISE MAGNETOMETERS ON BASE OF PULSED NMR TECHNIQUES

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Abstract

A series of precise magnetometers on base of pulsed Nuclear Magnetic Resonance (NMR) techniques has been developed in BINP. In the field range of 0.025÷13T an error of homogeneous magnetic fields measurements does not exceed $(5\div10)\times10^{-6}$, resolution is better than 10^{-7}. The magnetometers provide automatic search of NMR signal and magnetic field tracking. One type of the magnetometers is able to work with aluminium powder as working substance of NMR probes. These probes can be used for measurements of magnetic fields at liquid helium temperature. A special NMR probe with very small sensitive volume (about 1 mm^3) has been designed to measure the fields with the gradient up to 150 G/cm. At present, NMR magnetometers developed and fabricated in BINP successfully work in some scientific centers in Russia and abroad. The features of the magnetometer's electronics design and most interesting examples of magnetometer's application in charged particle storage rings are presented.

INTRODUCTION

Nuclear Magnetic Resonance (NMR) magnetometers on base of pulsed NMR techniques have been developing in BINP since 1986 [1,2]. In 1999-2006 a new generation of precise magnetometers on base of pulsed techniques in VME and CAMAC standard has been developed and fabricated [3,4,5]. Main features of the magnetometers are:

- High precision – field measurement error does not exceed 10^{-5}, resolution is better than 10^{-7} (for homogeneous fields).
- Wide field range: 0.025-13T.
- Large field range provided with one probe: B_{MAX}/B_{MIN} is up to 30.
- Acceptable field gradients – up to 15 G/mm.
- Possibility of multichannel measurements.
- Small probe dimensions – the minimal probe thickness is about 1 mm.
- Small probe sensitive volume – up to 1 mm^3.
- Capability of field measurements at a liquid helium temperature.

NMR TECHNIQUE

Operation principle of all NMR magnetometers is based on the measurement of the Larmor frequency of nuclei precession:

$$\omega_L = \gamma \cdot B,$$

where γ is gyromagnetic ratio, B is field induction.

Pulsed technique used in our magnetometers [4] is shown in Fig.1.

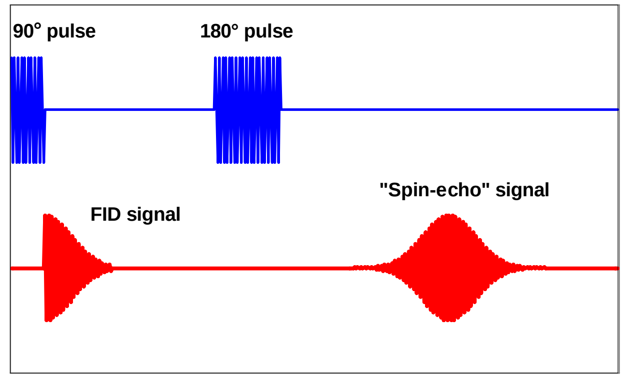

Figure 1: Basic NMR technique.

Nuclei of probe working substance are excited by two radio frequency (RF) pulses. Either free induction decay (FID) signal or spin echo signal is registered by magnetometer's electronics. After analog and digital signal processing Larmor frequency is found.

STRUCTURE AND OPERATION PRINCIPLE

A functional diagram of the magnetometer is represented in Fig.2.

The magnetometer consists of NMR probes with head electronics, Probe Multiplexer, RF pulses generator, receiver circuit, frequency Synthesizer and control circuit. NMR probes consist of only passive components. Probe head electronics is mounted in separate body at a short distance from the probe (0.5÷3 m). Head electronics amplify the weak probe signals (with amplitude 1÷50 μV) in 40 dB and commutate the RF pulses to the probe. Probe Multiplexer (CAMAC or VME module) allows the measurements with one magnetometer the fields at different points. Amplified NMR signals of chosen probe come to Receiver circuit where they are mixed with two orthogonal Synthesizer voltages. After sampling with ADC of the two orthogonal NMR signals with low frequency $F_D = F_{NMR} - F_{SYNT}$ a digital signal processing is performed in VME or CAMAC Controller. The final result of this processing is the absolute value and sign of the frequency F_D. To minimize the influence of the noise on the measurement result matched filtration is used in digital signal processing.

The magnetometer has two modes of operation: measurement mode and search mode. In the search mode a coarse value of NMR frequency is finding by scanning of the Synthesizer frequency in specified range. In the measurement mode NMR frequency is found with maximal precision, the Synthesizer frequency follows the measured field.

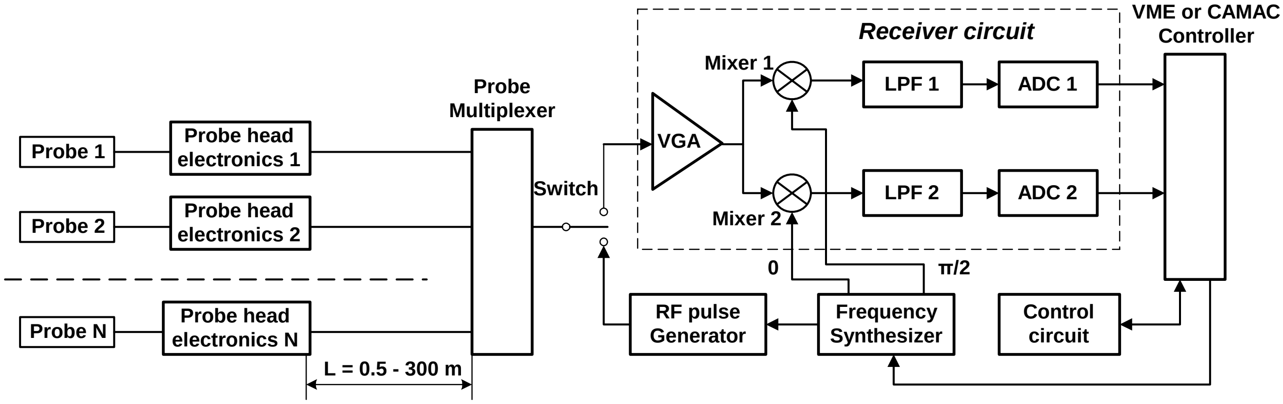

Figure 2: Functional diagram of NMR magnetometer.

The whole cycle of the magnetometer operation in the measurement mode consists of two actions: signal accumulation and digital signal processing. During signal accumulation N digital arrays of the sampled NMR signals are summed. It leads to increasing by $\sqrt{N}$ of the signal-to-noise ratio. Simultaneously with signal accumulation digital processing of the signal obtained in the previous cycle is performed.

Important parameter of the magnetometers is "dead time" T_D – time interval after the end of RF pulse needed for recovery of the receiver circuit. Smaller T_D value allows working with shorter FID signals. Since smaller T_D values lead to more complicated electronics two modifications of the magnetometers have been developed: magnetometers with $T_D \approx 3\div5$ µsec and magnetometers with $T_D \approx 100$ µsec.

NMR PROBES

NMR probes consist of only passive components: working substance sample located within a coil and probe body. Narrow bandwidth probes can contain one or two capacitors. A variety of tasks solved with NMR magnetometers leads to the variety of NMR probes. Various working substances are used by authors for NMR probes: water, rubber, lithium salts, heavy water and aluminium powder.

In most probes the protons are used as working nuclei due to high signal-to-noise ratio. Metal aluminium powder is used for measurements at liquid helium temperature [3]. Main disadvantage of metal working substances is low spin-spin relaxation time T_2 which for aluminium is ~40 µs. This limits a precision of field measurements and requires a small "dead time" value (a few microseconds) of the magnetometer's receiver circuit.

The probe sensitive volume (working substance volume located within the coil) is usually optimized for each application. For measurements of less homogeneous fields less sensitive volume is used.

ACCURACY

RMS NMR frequency error can be estimated with following simple expression [4]:

$$\sigma_F \cong \Delta F_S /(S/N)_F , \qquad (1)$$

where ΔF_S – is width of signal spectrum,
$(S/N)_F$ – is signal-to-noise ratio in frequency domain.

Width of signal spectrum consists of two main components:

$$\Delta F_S \cong 1/T_2 + \gamma\cdot\Delta B/\pi , \qquad (2)$$

where ΔB – is field dispersion within the probe sensitive volume, T_2 – is spin-spin relaxation time of working substance.

As one can see the resolution of measurements depends on the measured field homogeneity. Increasing of measured field gradient leads to increasing of σ_F. For homogeneous fields with gradients $grad(B)/B$ less than 10^{-4}/cm in the range 0.1÷13 T the resolution is of order $10^{-7}/\sqrt{Hz}$. For NMR probes with aluminium working substances in the range 1÷13 T the resolution is of order $10^{-6}/\sqrt{Hz}$ due to low value of the spin-spin relaxation time T_2.

APPLICATION

VEPP-4

At VEPP-4 storage ring (BINP) NMR magnetometer performs 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. Monitoring of bending magnets fields gives the information about the beam energy behavior during the experiments. This became especially important after beginning in 2002 at VEPP-4 a series of precise experiments. NMR signal obtained with the probe at the magnet "H" on the beam energy 1840 MeV is shown in Fig.3.

The width of NMR signal spectrum defined by field homogeneity in the range 0.1-0.6 T is $(2\div3)\times10^{-5}$. Taking into account that signal-to-noise ratio in specified range with measurement time 1 sec is 500÷1000 the resolution of measurements is less than $10^{-7}/\sqrt{Hz}$.

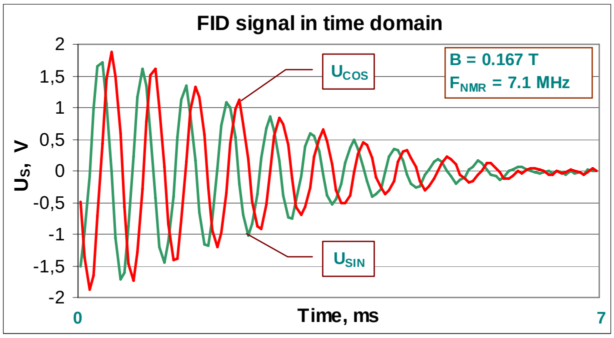

Figure 3: NMR signal in the magnet “H” on the field 0.167 T.

Using of NMR magnetometer in VEPP-4 helps to increase the accuracy of the measurements of mass J/ψ, ψ', ψ''.

VEPP-2000

At electron-positron collider VEPP-2000 (BINP) NMR magnetometer is developed for measurements of magnetic fields of all eight main bending magnets. NMR probes are set in median plane of each magnet at the side of vacuum chamber (Fig.4).

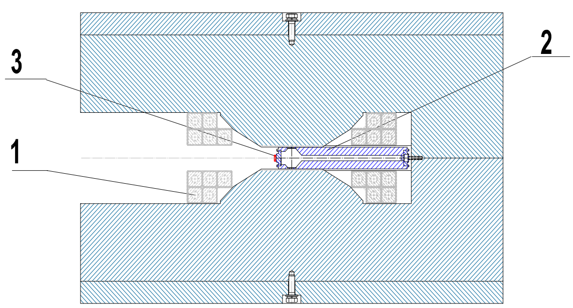

Figure 4: Cross-section of VEPP-2000 bending magnet: 1 – coil, 2 – vacuum chamber, 3 – NMR probe.

The main problem is a large field gradient in the probe volume – up to 120 G/cm at maximal field ~2.4T. To achieve acceptable width of signal spectrum special NMR probe with small sensitive volume (about 1 mm^3) has been designed. The measured signal spectrum in the field range 0.3÷2.4 T obtained with this probe is $(1\div2)\times10^{-4}$. As a result the resolution of measurements better than $10^{-5}/\sqrt{Hz}$ is achieved.

Electron Cooling Facility

At Fermilab electron cooling facility NMR magnetometer is used for field stabilization of ten bending magnets of transport system. Field range is 260÷360 G for eight 45-degree bending magnets and 400÷500 G for two 90-degree bending magnets. The main problem of measurements of such low fields is small signal-to-noise ratio. Optimization of NMR probe and receiver electronics allows the authors to achieve of acceptable resolution of measurements – better than $10^{-6}/\sqrt{Hz}$. With using of NMR magnetometer field stability of order 10^{-6} was demonstrated (Fig.6).

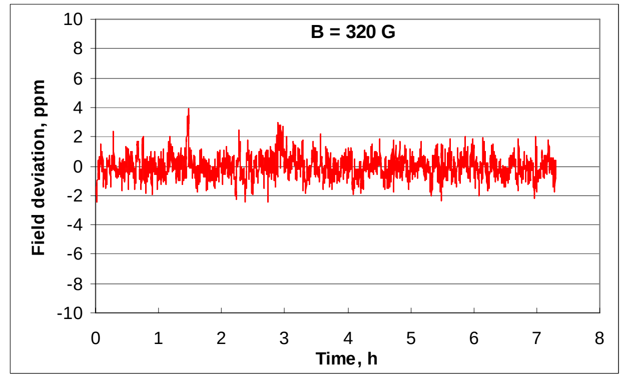

Figure 5: Results of field stabilization of 45-degree magnet (field is measured with another NMR magnetometer).

Superconducting Wave Length Shifters

In superconducting wave length shifters (WLS) developed and constructed in BINP for BESSY-2 and SpRing-8 NMR magnetometers are used for the measurements and stabilization of the central poles field [3,5]. NMR probes have been installed within liquid helium volume inside the WLS central poles in the points with maximal field homogeneity. Aluminium powder has been chosen as working substance for NMR probe. High signal-to-noise ratio due to increasing of nuclear magnetization at ultra low temperatures allows us to use a small probe sensitive volume – about 2 mm^3. As a result in spite of field gradient in the probe site up to 3÷5 G/mm the resolution of measurements in the working range (5÷7 T for BESSY-2 WLS and 7÷10 T for SpRing-8 WLS) is not worse than $(1\div2)\times10^{-6}/\sqrt{Hz}$.

SUMMARY

Developed in BINP new generation of the NMR magnetometers allows us to solve some difficult tasks on precise field measurements at storage rings and magnetic measurements stands. Since 1999 ten magnetometers have been fabricated and successfully implemented at BINP, Fermilab, Duke University, BESSY-2, SpRing-8.

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