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RADIATION PROOF MAGNETIC FIELD METER

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1. Introduction

To quickly set up a previously attained operation regime on the future USPIF Microtron accelerator it is necessary to reproduce the beam trajectory in the main microtron magnets and in the bend magnets of the beam transport system. This means that it is necessary to accurately (better than 0.1%) reproduce the magnetic field absolute values in all dipole magnets. Usually, a system of magnetic field measurement based on the nuclear magnetic resonance (NMR) method is used for this purpose.

The system is very convenient for accelerator tune-up, since, in this case, the tuning can be performed by means of a determinant parameter (magnetic field intensity), using instead of a secondary reading like current in coils. An important characteristic of the measuring system is to be radiation proof, i. e., the electronics associated with the magnetic probe has to stand high radiation levels of the environment without loss of performance.

This paper (i) describes a magnetic field meter, based on the NMR method, which is an updated version of a similar one developed at the Kharkov Institute of Physics and Technology (Ukraine) [1,2] and (ii) discusses the need of such a system for accelerator control, presenting results of measurements performed on one of the recirculating magnets of the microtron booster.

2. The NMR Method

The phenomenon of NMR can be described as follows [3]: the magnetic moment of a nucleus, when placed in a steady and uniform magnetic field H_0, has precession around the direction of this field with frequency: $\omega_0 = y \cdot H_0$ (Larmor precession). This frequency is directly proportional to the applied magnetic field, H_0, and to the gyromagnetic ratio, y, which is different for each nucleus and known with high accuracy. If, besides the main steady field, a small rotating magnetic field with frequency ω is applied in a plane perpendicular to the direction of the main field, then the magnetic moment of the nucleus will be submitted to an additional force, which tries to change the angle of precession. If there is no synchronism between the secondary field and the precession of the magnetic moment, this force will be changing in magnitude and direction and will have no net effect on the average. On the other hand, when the frequency ω of the secondary magnetic field H_1 coincides with the Larmor frequency of precession, there is synchronism and a resonance process occurs. There is absorption of energy from the field H_1 and the angle of precession is changed. The new character of the motion of the magnetic moment is equivalent to a change in the magnetic susceptibility of the substance (χ). In a quantum mechanical approach this means that the projection of the magnetic moment is changed.

In practice, instead of a rotating field, a linearly polarized magnetic field, resulting from the passage of RF electric current through a coil, is used.

The phenomenon of NMR has several applications in technology and medicine [3,4] and, in particular, it is used for high precision absolute measurements of steady and uniform magnetic fields. Usually, the measurement of a magnetic field is based on proton NMR, using water as a working substance, containing some dissolved paramagnetic salt to shorten the spin-lattice relaxation time. In this case the NMR signal to noise ratio is maximum. For very intense fields it is better to use NMR on Li nuclei (working substance LiCl) in order to reduce the working frequency. Table 1 shows the characteristics of some working substances commonly used.

Table 1

Nucleus	Substance	NMR frequency (MHz) for 10 KG field	Relative sensitivity at constant field
p	H^2O	42.5759	1.00
D	D^2O	6.53566.	$9.65 \cdot 10^3$
^{7}Li	LiCl	16.5466	0.293
Al	AlCl	11.0945	0.206

An important requirement of the magnetic field to be measured is its uniformity, since in an inhomogeneous field the NMR signal becomes broad because several different frequencies contribute, weakening the signal and causing loss of accuracy. For high accuracy measurements the field gradient should be less than 10 gauss/cm.

3. Construction of the magnetic field meter

The magnetic field meter (Fig.1) consists of an external block with the NMR probe connected to the control system and power supplies. An oscilloscope and a frequency counter are used as output blocks. The NMR probe consists of a small glass cylinder filled with the working substance (H_2O + 1-2% FeCl3) and surrounded by (i) two small RF coils (two working ranges), orientated in such way that they produce a linearly polarized RF field perpendicular to the main field; and (ii) one big coil which modulates the main magnetic field at a low audio frequency with an amplitude up to a few gauss.

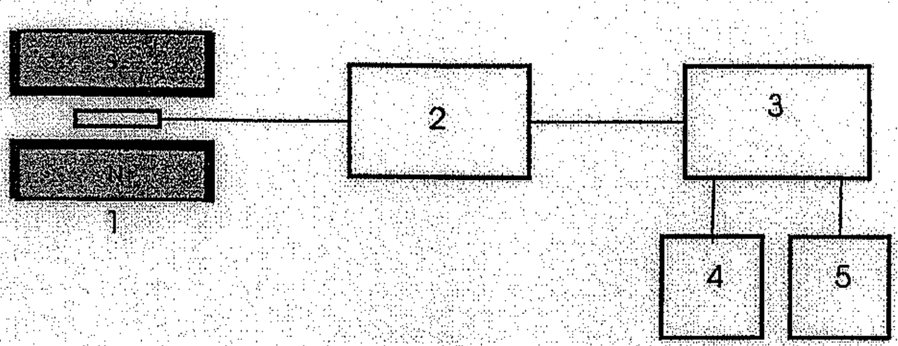

Fig.1. Block diagram of the magnetic field meter.
1 is a magnet field to be measured, 2 is the external block, 3 is the control system, 4 is an oscilloscope, and 5 is the frequency counter.

The external block (Fig. 2) consists of:

- Autodynes of Pound and Knigh (first range: tubes Tu_1 and Tu_2; second range: tubes Tu_3 and Tu_4)
- RF amplifer (Tu_5, T_3-T_5)
- Audio frequency (AF) amplifier (Tu_6 and Tu_7, T_1 and T_2)

The use of miniature metal-ceramic tubes (Tu_1-Tu_7), which are characterized by low intrinsic noise level and low interelectrode capacitance, in the first and most sensitive cascades of the RF and AF amplifiers presents several advantages: increases the NMR signal to noise ratio; increases the working frequency range; improves the reliability; and keeps the circuit radiation proof.

The control system (fig.3) consists of:

- Phase shift circuit,
- Audio frequency modulation block (tuning of the field modulation amplitude),
- Block of the RF fine tuning
- Block for the tuning of the RF field amplitude,
- Power supplies (6 V, 1 A; 27 V, 100 mA).

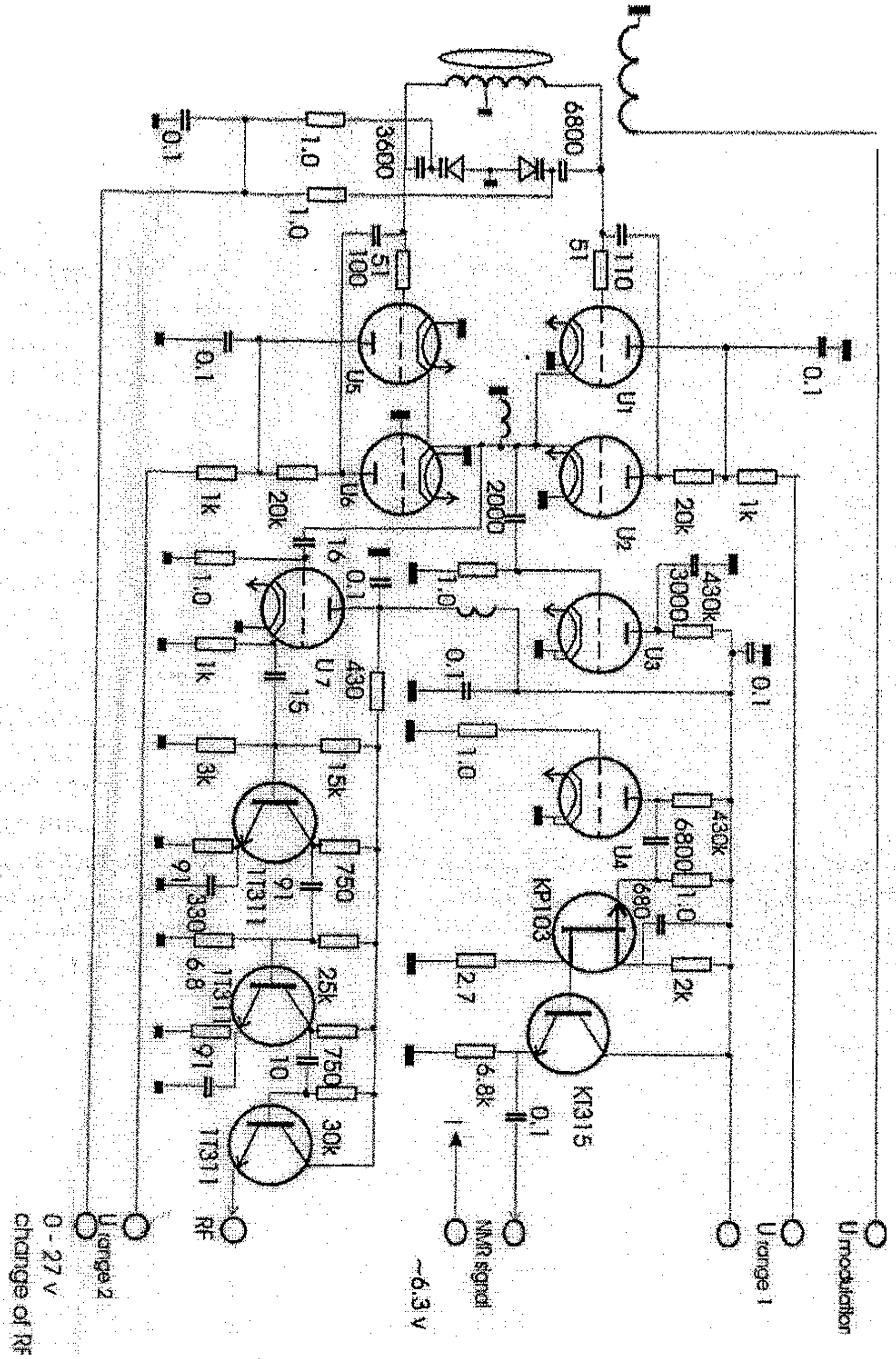

Fig.2. Schematic diagram of the external block.

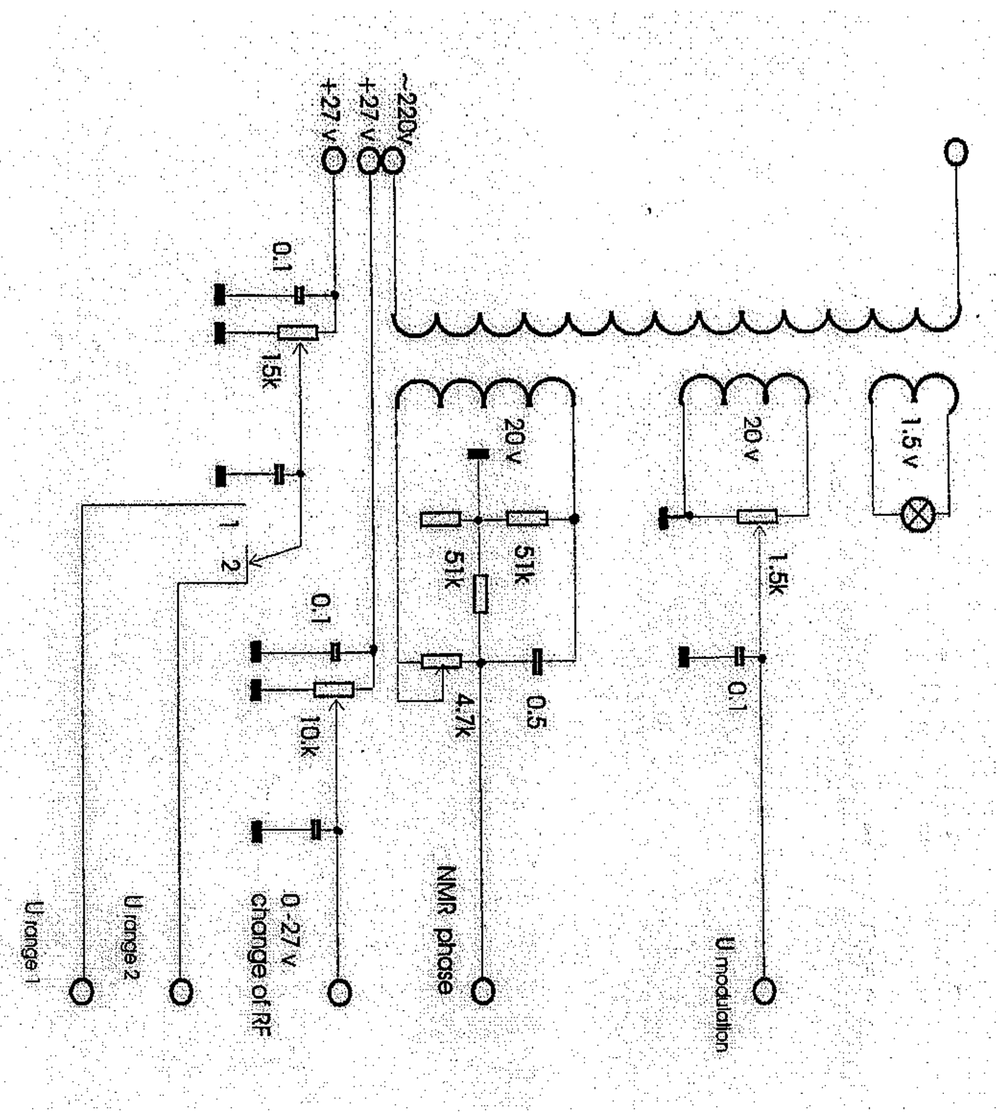

Fig.3. Schematic diagram of the control system circuit.

4. Working characteristics

When the probe is placed in a magnetic field it becomes subject to:

- main magnetic field modulated at a low audio frequency,
- RF linearly polarized field, oriented perpendicularly to the main field. .

When the tunable RF frequency coincides with the precession frequency of the proton (twice during one period of modulation, see fig. 4) the NMR process occurs and the

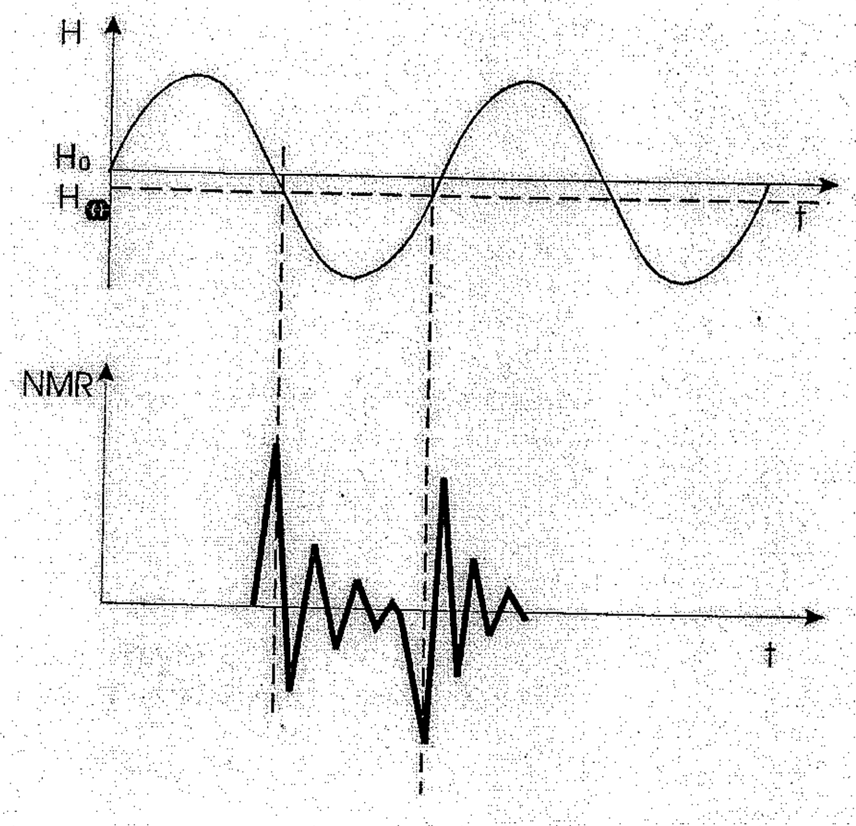

Fig.4. Schematic diagram of the passage of MNR through the audio modulated magnetic field.

magnetic susceptibility of the working substance is changed. Consequently, the inductance of the RF coil is changed and RF power is absorbed, producing an AF amplitude modulation of the RF signals. After rectification (demodulation) the audio NMR signal is further amplified and finally displayed on the oscilloscope. The frequency counter records the RF frequency corresponding to the NMR. In a more sophisticate set up, the NMR signal can be digitized and used as one of the parameters in the control system of the accelerator.

The main characteristics of the system are described below:

RF range: 0.65-85 MHz.

RF stability: better than $5\mathrm{x}10^{-5}$/hour.

Range of magnetic field (for NMR on protons): 0.014-2 T.

Magnetic field uniformity: better than 10^{-4}T/cm.

Accuracy (average over the probe volume): $\Delta B/B \approx 10^{-5}$.

5. Tests and results

To test the accuracy of the system, we made several measurements of the same field (fixed probe, stable temperature of the magnet, current fixed and total measuring time not exceeding 20 min.): we found the resonance, recorded the frequency and then messed up all the controls to restart the procedure again, finding the resonance, recording the frequency and so on. The distribution of 59 measurements performed in this way was fitted by gaussian and with a reduced chi-square of 0.37384, showing a standard deviation for the $\Delta f/f$ distribution of 2.5×10^{-6}, an excellent result for our purposes.

The dependence of the resonance frequency (which is proportional to the magnetic field) versus the current in the coils of the booster magnet, for the regime of adiabatic increase of the current, shows a good linearity and far from saturation effects. The working frequency (4.683 MHz) is in the middle of the range.

The measurements of magnetic fields for both

1. regime of adiabatic increase of the current,
2. regime of adiabatic decrease of the current, reproducing the values of current for the previous regime of the measurement, show that the effect of hysteresis ($\Delta H/H$) for this regime of installation of the working current is about 3×10^{-3}.

The results of measurements of the reproduction of magnetic field for quick (non adiabatic) on/off switch of the power supplier current, show that the accuracy of reproduction is about 2×10^{-4}, but some points have bigger deviation, up to 7×10^{-4}.

The adiabatic reproduction of the working current from any on previous value (maximum possible spread) shows that the accuracy of the reproduction for any possible way is better than $\pm 1.6 \times 10^{-3}$.

6. Conclusions

The test of the magnetic field meter we developed demonstrates the high stability of its main working characteristics.

The measurement of the reproduction of an absolute value of magnetic field of on of the booster magnets shows the low hysteresis effect.

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